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THESIS

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THE DESIGN AND IMPLEMENTATION
OF A POSITION MEASURING SYSTEM FOR
A REMOTELY CONTROLLED VIDEO CAMERA

by

Peter D. Lloyd

June 1989

Thesis Advisor: Alfred W. Cooper
Co-Advisor: Hal A. Titus

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The Design and Implementation of a Position Measuring System for a Remotely Controlled Video Camera

by

Peter D. Lloyd
Captain, United States Marine Corps
B.S., United States Naval Academy, 1979

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1989

ABSTRACT

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THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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I. INTRODUCTION

A. BACKGROUND

The old saying that "every solution breeds new problems", while somewhat pessimistic, quite often rings true in today's increasingly technical world. One such example is the use of infrared (IR) sensors for the detection, tracking and/or identification of targets in a combat environment. IR sensors are ideally suited for use on today's battlefield. They are passive, i.e., they do not need to emit energy in order to detect the presence of potential targets. This allows them to operate during times of emission control when many other target detection systems are useless. They have the ability to "see through" many forms of camouflage and concealment, dust, clouds, smoke, etc., that might otherwise afford an enemy target a safe haven. Additionally, because almost everything on today's battlefield generates some degree of infrared energy, IR sensors can be used to locate and identify a wide variety of targets.

The extent to which a particular IR sensor is useful depends primarily on its ability to detect and identify targets reliably and accurately. Detection of the target is primarily a function of the IR sensor's sensitivity. The classification of a received IR signal as a potential target or as background noise, while still dependant on the sensitivity of the sensors, is primarily a function of the quality of the signal processing algorithms being used to process the received signals. In addition to being reliable these algorithms must be able to process the received signals in "real time" if the system is to be an effective weapons system.

Creation of a background data base that can be used to test some of these algorithms has been one of the tasks being performed by the Naval Academic Center for Infrared Technology (NACIT) located at the Naval Postgraduate School (NPS). The Advanced Development Model (ADM) of the AN/SAR-8 was sent to the NACIT in January of 1984 from the Naval Surface Weapons Center (NSWC) at Dahlgren, Virginia. The ADM was modified, calibrated and placed in service at NPS in December, 1987. The modified version of the ADM, the Infrared Search and Target Designation (IRSTD) System, is currently operational at NPS. [Ref. 1: pp. 8-12]

One way to enhance the usefulness of the IR data being collected at NPS would be to collect video data concurrently with the IR data. A video image of a portion of the horizon would permit visual identification of IR sources in that region. This additional

tional information could be an aid in the development of the signal processing algorithms for the IRSTD. Accordingly, a decision to proceed with video data collection was made by NACIT, and a camera system was purchased. Components of the system include;

- RCA (TC1005/01), Closed circuit video camera.
- PELCO (AI700), Automatic iris servo.
- PELCO (F1.5X), 1.5 times range extender.
- PELCO (MLZ6DT), Desk top lens remote control module.
- PELCO (PT1250DC), Heavy duty Pan/Tilt servo.
- PELCO (MPTV1510DT), Pan/Tilt remote control unit.
- Panasonic (WV-5410), Video Monitor.

In Ref. 1 Ayers describes the IRSTD's detectors:

> The IR detectors consist of two vertical arrays of sensing elements in the focal plane of the Schmidt telescope. The telescope is rotated so as to sweep the image across the detector arrays. Each array incorporates a column of 90 indium antimonide photovoltic linear detector elements. These two arrays are independent of each other and are covered by filters which pass selected wavebands of IR radiation in the 3 to 5 micrometer range. Each element has the angular dimensions of 2 X .3 milliradians with the larger being its height. Designated as the lead and the lag, these two arrays are separated by about one-half degree in azimuth. [Ref. 1: p. 17]

Thus, as the IRSTD scans the horizon the resulting IR image has a resolution of approximately 10^{-4} radians (0.00573°) in the horizontal plane and 0.23° in the vertical plane. The video system's smaller field of view can be remotely controlled using the control units listed above. Thus, for the video data to be of any use in the development of the signal processing algorithms, the camera's orientation must first be known, and, in order to determine the pixel-to-pixel correlation between the IR image and the video image, the position of the video camera needs to be known with the same kind of accuracy as the IR image. The design and implementation of a position measuring system for this remotely controlled video camera is the subject of this thesis.

B. DESIGN SPECIFICATIONS

The design specifications for this problem were relatively straight forward. The position measuring system needed to meet the following criteria.

- The system should be able to measure the elevation angle (tilt), above and below the horizontal reference plane of the camera over a range of $\pm$ 12°.
- The measured elevation angle should be accurate to within $\pm$ 0.23° .

- The system should be able to measure the bearing (pan), left or right of some arbitrary reference, of the camera over a range of 360°.
- The measured bearing should be accurate to within $\pm 10^{-4}$ radians.
- The output should be displayed in a convenient form. The display should be collocated with the camera servo remote controls, an indoor site approximately 200 meters away from the camera.
- Portions of the measuring system required to be collocated with the camera should be weatherproofed.
- The system must be reliable and should be simple to operate.

II. DESIGN STRATEGY

A. GENERAL

A position measuring system, like any system, is a combination of devices interconnected to perform a certain function. The most basic position measuring system (see Figure 1) consists of only four such devices: a transducer, a signal conditioner, a display device and a power supply. More complicated position measuring systems include those designed to take a number of different measurements either simultaneously or consecutively. Still more complex systems multiplex these various measurements over a single channel to some distant location where they can be processed and displayed. [Ref. 2: pp. 2-14]

The design specifications for the camera position measurement system (subsequently referred to as the "measurement system") required that two measurements, pan and tilt, be taken simultaneously and transmitted some distance to a remote display. Two separate transducers, capable of independent operation, were therefore required. In order for both the azimuth and the elevation to be displayed simultaneously two display devices were also required.

Several pairs of RG-178 coaxial cable were available to transmit signals between the camera servo and the remote control site. Since the cable was available and it was desirable to reduce the system complexity, a decision was made not to multiplex the data over a single channel. Instead, each measurand would have a separate transducer, a dedicated signal processor and a unique display device. Position information for each axis would be transmitted over a dedicated channel.

The physical locations of the transducers and the display devices were dictated by the design specifications; however, there was some flexibility in deciding where to locate the signal conditioner. Site selection was based on an attempt to maximize total system performance and simplicity while ensuring the maintainability and environmental integrity of the signal conditioner. The only advantage to locating the signal conditioner with the camera servo and the transducer would have been to limit the distance that the transducer's output signal would have to be transmitted to the processor. On the other hand, separating the signal conditioner and the transducers would limit the distance over which the conditioned signal would have to be transmitted to the display device. The trade-off here was not clear cut and would probably depend on the specific hardware

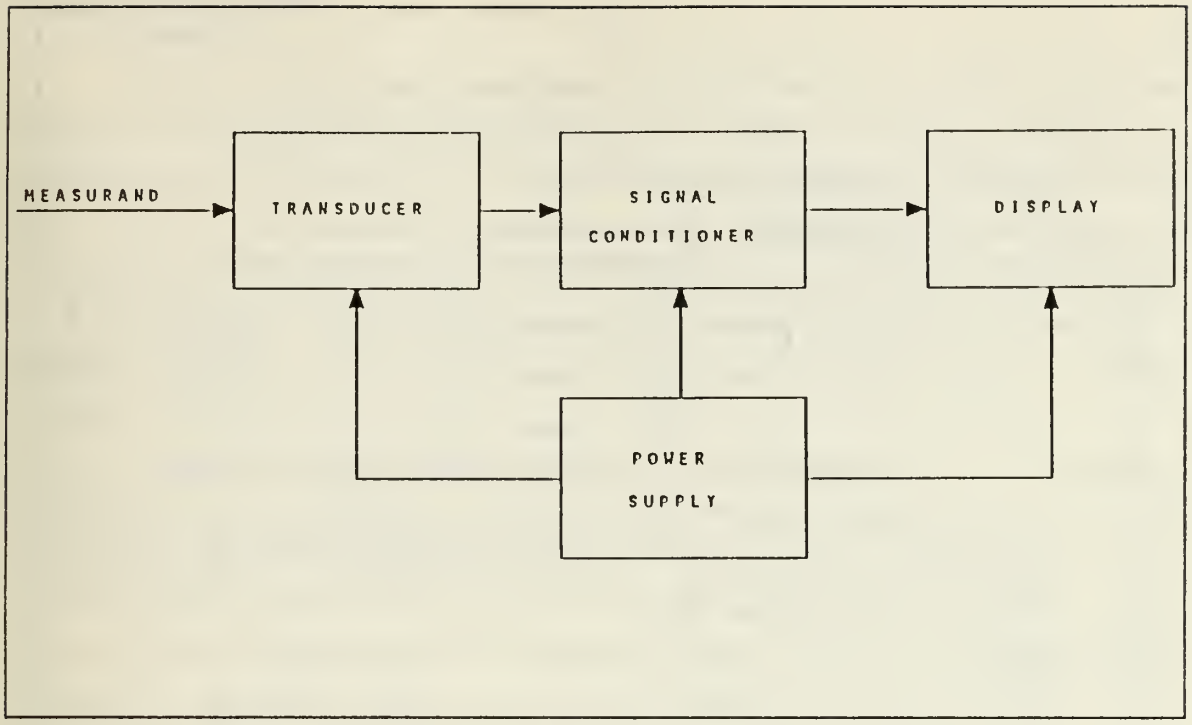


Figure 1. Basic Electronic Position Measuring System: From Ref. 2: p. 2

used and the speed of rotation of the camera servo. There was one significant advantage, however, to collocating the display and the signal processor; since they would both be indoors, the need for weatherproofing the signal processor would be eliminated.

Power was available at both ends of the system, there was therefore no requirement to have a common power supply for the entire system. One supply could be used to provide power to the two transducers, collocated with the camera servo, and a second supply could power the signal conditioner and the displays.

A block diagram of the prototype measurement system is shown interconnected with the camera positioning system in Figure 2. Once this basic system layout had been determined, proper selection of the actual hardware was necessary. The design criteria were the primary consideration in the initial stages of the hardware selection. Final selection of the specific components, however, involved balancing additional factors, such as availability and cost against the system requirements.

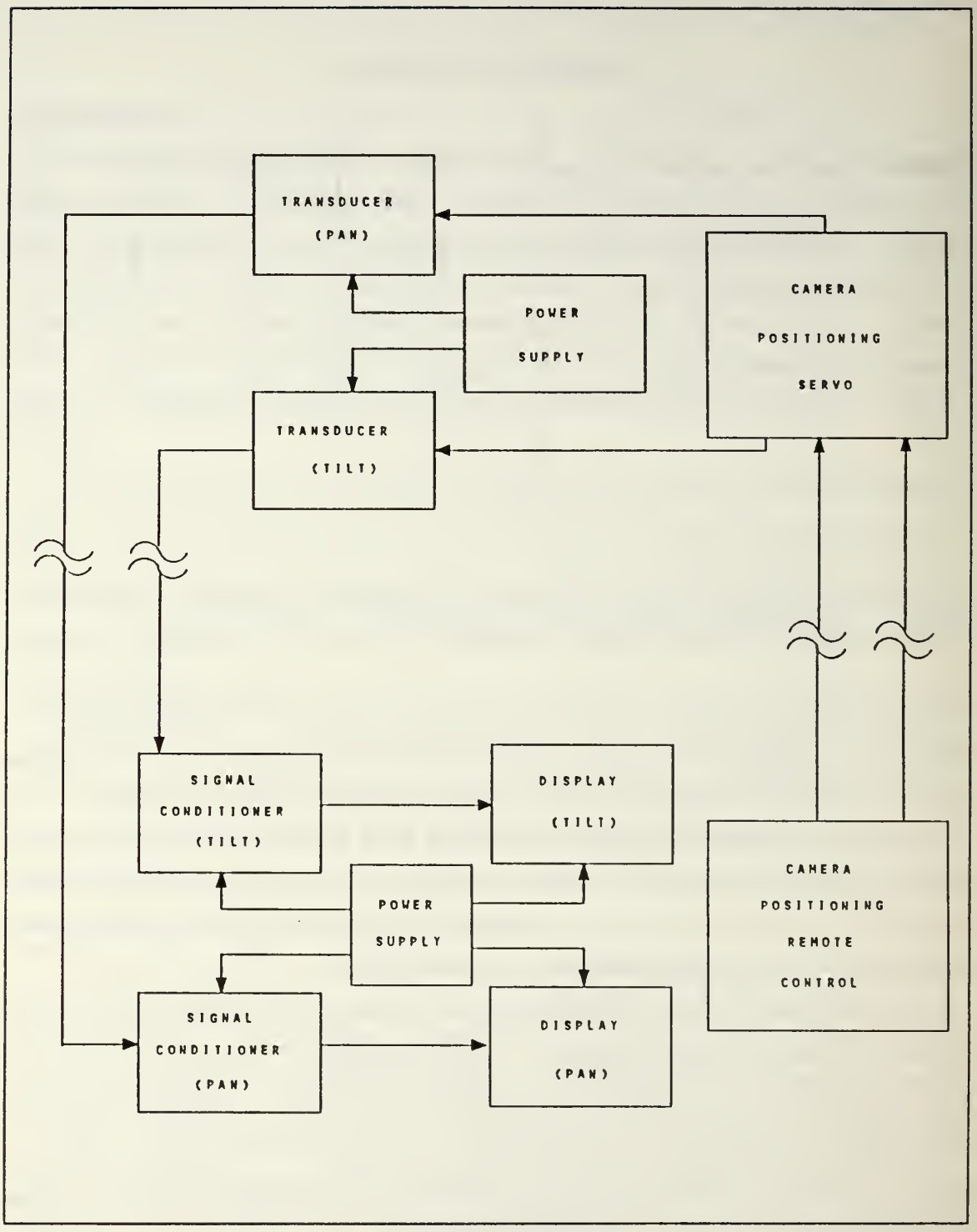


Figure 2. Camera Position Measuring System

B. TRANSDUCERS

1. General

Since in practice most measurement systems do not have the ability to respond directly to the measurand, transducers are used to convert one physical quantity (e.g., angular position) into another, more usable quantity or signal (e.g., an electrical signal) [Ref. 3: p. 1-4]. The transducer is therefore a vital part of any measurement system, and although none of the components of this system could have been chosen independently of the other elements, proper transducer selection appeared to be the key to meeting the design specifications. Thus, selection of a transducer was the next step in the design process.

Using the selection guidelines given by Norton on pages 51-53 of Ref. 2 and the design criteria stated previously, several observations and decisions were made which significantly reduced the number of transducers considered feasible for use in the measurement system. The fact that the servo was capable of rotating the camera left or right, and up or down suggested that the transducer should be capable of detecting both increasing and decreasing angles on both axes. Additionally, since the servo was anticipated to rotate the camera through one 360° arc in the horizontal plane, the transducer used to measure this angle (subsequently referred to as the "pan transducer") needed to have a comparable range capability. The range requirement for the "tilt transducer" (used to measure the elevation angle) was much less restrictive. These factors, angular bidirectional capability and full scale range, eliminated a great number of transducers from the list of candidates.

The list was further narrowed by the accuracy requirements previously specified. Again the accuracy in the horizontal plane placed a much more severe limitation on the selection of a transducer than the accuracy requirements for the vertical plane. The following paragraphs in this section outline the logic used in the selection of the transducers. The factors considered in the selection process included the following;

- The accuracy requirements given in the specifications.
- The ease with which a specific transducer could be installed on the servo.
- The ability to weatherproof the servo and the transducer once the transducer was installed.
- The rotation speed of the camera about the servo axes.
- The extent to which a particular transducer/mounting configuration would modify the measurand.
- Cost effectiveness.

- Availability.
- Signal conditioning requirements.
- The extent to which the selection of a particular transducer would simplify or complicate the modification or expansion of the measurement system.

2. Transducer technologies

Displacement transducer technologies fall into three very broad categories depending on whether they are capable of measuring linear or angular displacement, or both. Some technologies could be eliminated immediately since they were clearly not suited for measuring angular position. Strain gauge displacement transducers, inductive displacement transducers and vibrating-wire displacement transducers are examples of such devices. The following paragraphs briefly describe the different transducer technologies which were investigated. Table 1 on page 18 summarizes the salient points of the discussion. [Ref. 2: pp. 90-117].

a. Reluctive Displacement Transducers

The rotary variable differential transformer (RVDT), which operates by detecting a change in the reluctance between coils, offers excellent resolution, dynamic characteristics, linearity and life expectancy [Ref.3: p. (2-14)]. Figure 3 shows a schematic diagram and a simplified cross-section of an RVDT. The ferromagnetic, cardioid-shaped core is attached to a shaft as shown. As the shaft rotates, the inductive coupling between the primary and each of the secondary coils changes. When the cam is symmetric with respect to the two secondary coils, their output voltages are equal but opposite in phase which results in a differential output voltage of zero. As the shaft rotates away from this "null" the differential output voltage varies as shown in Figure 4. The linear region of the curve is limited to the angles between $\pm 40°$ of the reference. Thus, the RVDT could not be used on the Pan axis. It was however, initially considered as a candidate for the Tilt transducer. [Refs. 2: pp. 93-99, 3: pp. (9-10)-(9-13) and 4: p. 19]

Another type of reluctive displacement transducer is manufactured by Farrand Controls. Their INDUCTOSYN rotary position transducers have accuracies to $\pm$ 1.5 arc sec ($\simeq(4 \times 10^{-4})°$). Unfortunately, these devices are 11.89 inches in diameter, and mounting them on the camera servo would have been extremely difficult, if not impossible. [Refs. 2: pp. 89-111, 5]

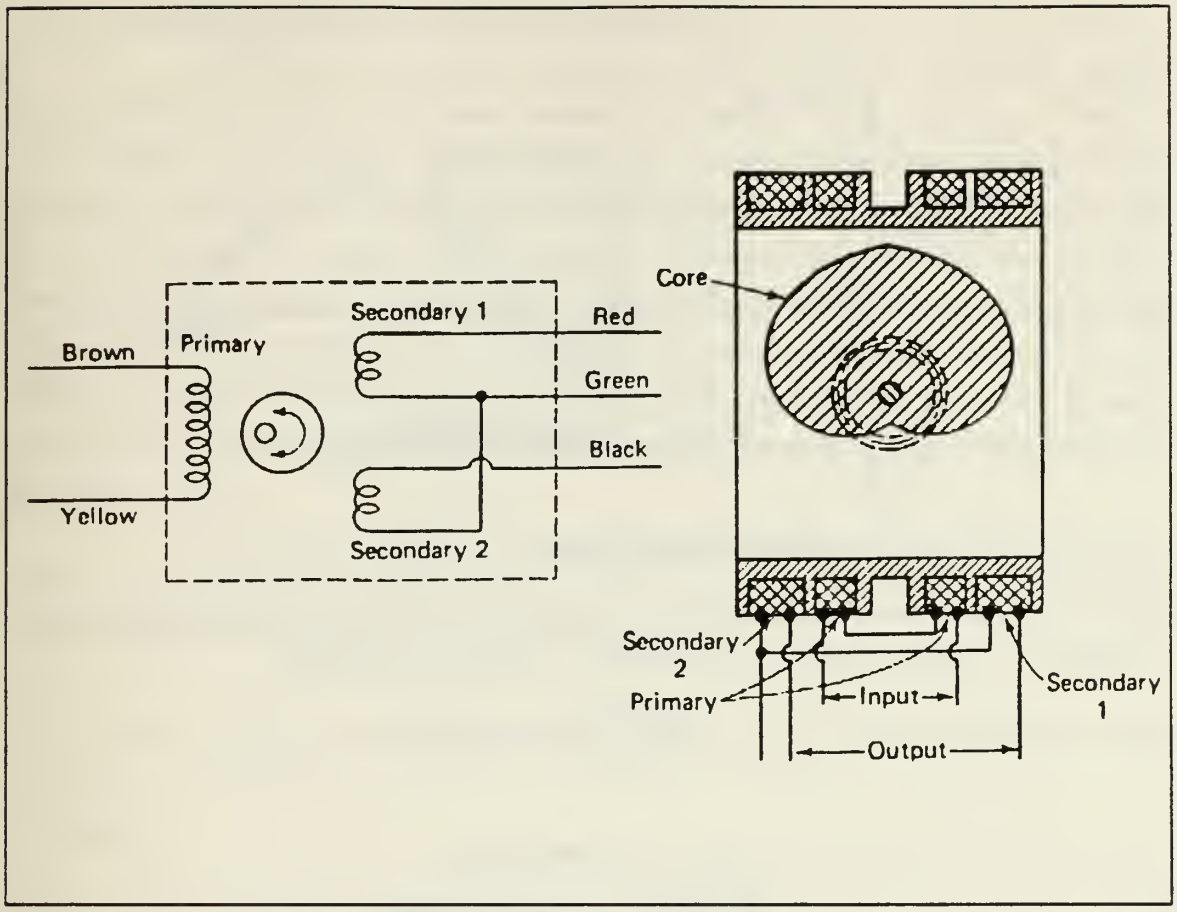


Figure 3. RVDT Schematic: From Ref. 2: p. 98.

b. Capacitive Displacement Transducers

Angular displacement can also be measured by coupling the rotating component to the shaft a of variable capacitor in the manner shown in Figure 5. Lenk describes the operation of the capacitive displacement transducer quite succinctly.

> The capacitor ... consists of a metal plate that moves between two fixed metal plates as a shaft is rotated. The three plates, and the air between them, form a capacitor with a capacitance that varies in proportion to the degree to which the plates are meshed. When the plates are completely meshed, the capacitance is at its maximum. When the plates are completely unmeshed, the capacitance is at minimum. [Ref. 4: p. 18]

Capacitive displacement transducers offer many of the advantages of reluctance displacement transducers. They have an effective range of about 300° which, while better than the RVDT's range, is still not adequate for the pan axis [Ref. 4: p. 18]. Additionally they are more sensitive to changes in the ambient temperature. Since the

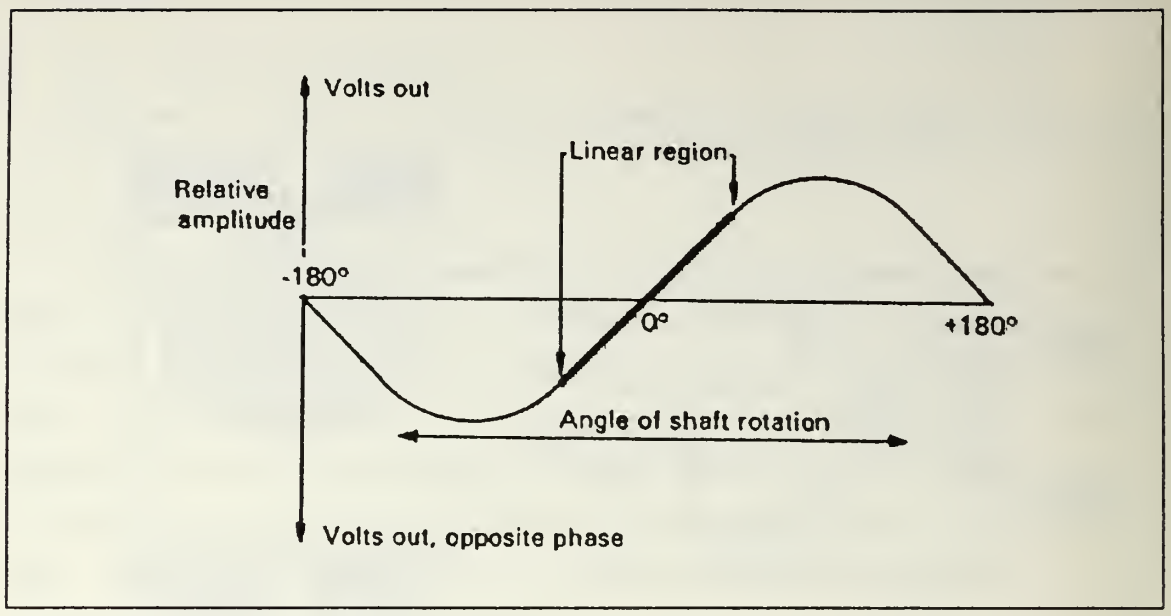


Figure 4. RVDT Output Characteristics: From Ref. 2: p. 95.

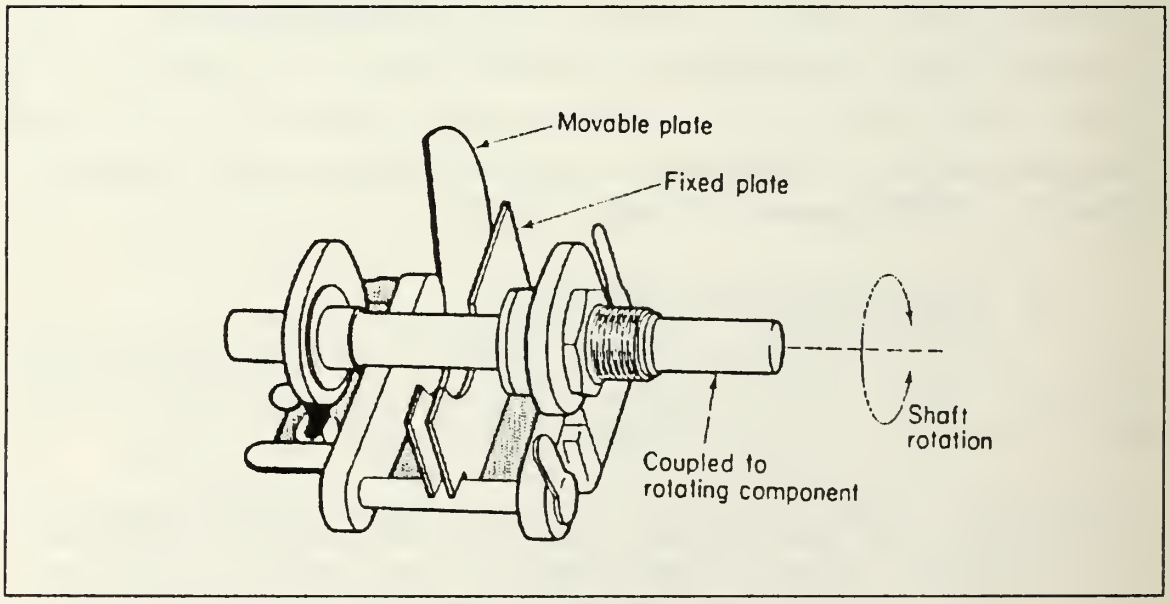


Figure 5. Capacitive Displacement Transducer: Ref. 4: p. 18.

measurement system was being designed to be used outdoors, the use of a capacitive displacement transducer would have required the addition of a temperature compensator in the design. While possible, this would have increased the system complexity considerably. [Ref. 2: pp. 90-91]

c. Potentiometric Displacement Transducers

Another very common and relatively simple family of transducers operate by measuring the change in resistance caused by a change in the measurand. There are a wide variety of such devices available. The basic form of potentiometric angular displacement transducers uses a resistance element, formed into an arc, and a movable electrical contact that rotates about the axis of interest. By measuring the change in resistance that results from a change in position, one is able to determine the angular displacement. The resistive element is typically a wirewound element, the resolution of which is determined by the number of turns per unit length of the resistance element. The angular resolution can be increased by increasing the turn density (wires/degree) of the potentiometer.

The practical limit for wire spacing on wirewound elements according to Ref. 6 is between 500 and 1000 turns per inch. From Figure 6 one can see that this limits the angular resolution for a single-turn device to

$$\Delta\theta(\text{rad}) \simeq \tan\left(\frac{\Delta x\,(\text{in})}{R(\text{in})}\right) \tag{1}$$

Therefore,

$$\Delta\theta(\text{rad}) \simeq \frac{2\Delta x}{D} = \frac{0.002(\text{in})}{D(\text{in})} \quad . \tag{2}$$

To achieve the 10^{-4} rad resolution, specified for the Pan axis, with a single turn potentiometer would therefore require a 20 in diameter potentiometer. Mounting a device this large on the camera servo was simply not feasible. Potentiometers are, however, available with multiple turns. Shaped in a helix fashion similar to that shown in Figure 7, the total length of the potentiometer can be increased, which in turn increases its resolution, without increasing the diameter of the device.

Increasing the resolution of the potentiometer by increasing the turn density in any of the manners described above, however, increases the output impedance of the device, which leads to increasing nonlinearity between the measurand and the transducer

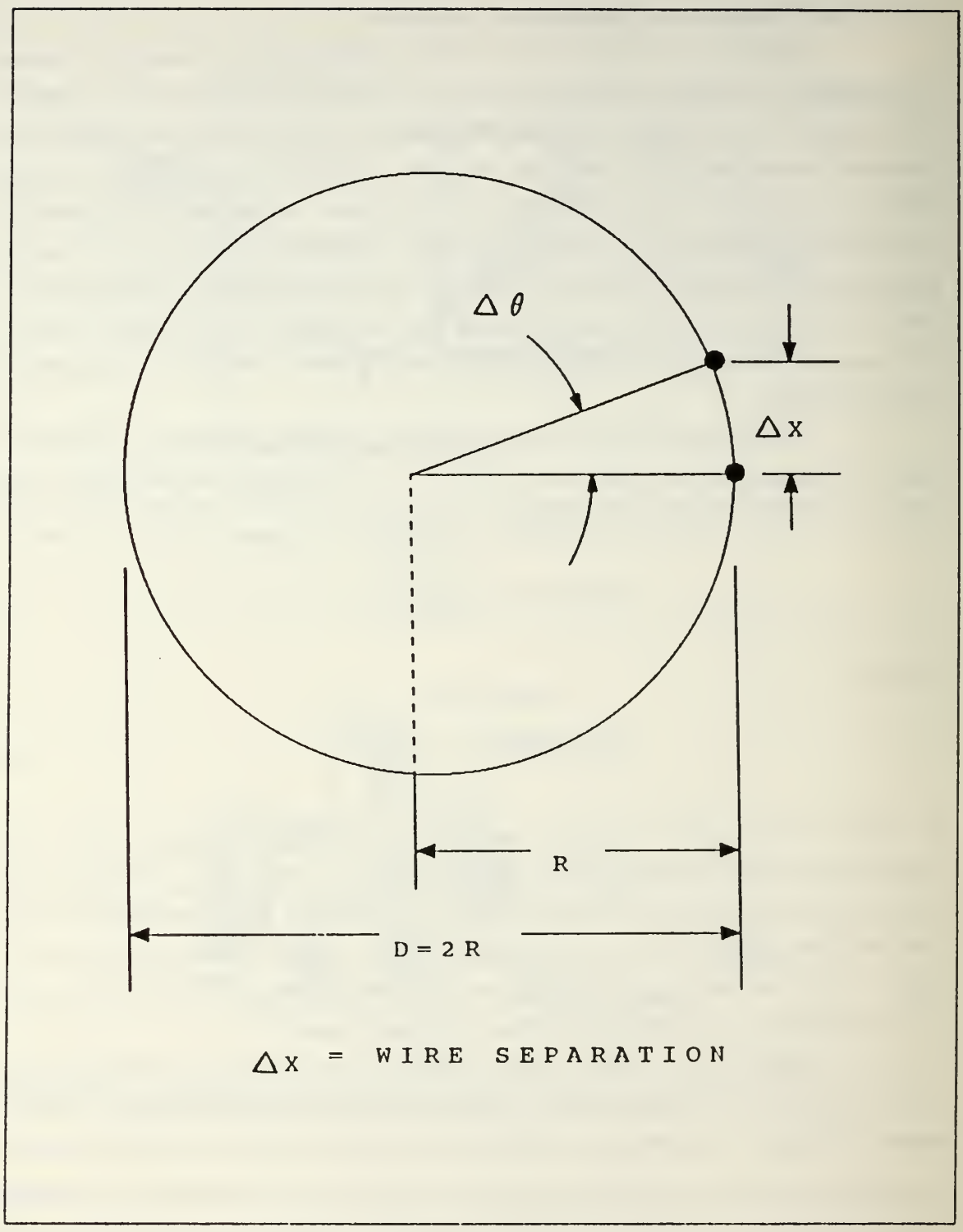


Figure 6. Geometry of an Angular Potentiometric Transducer

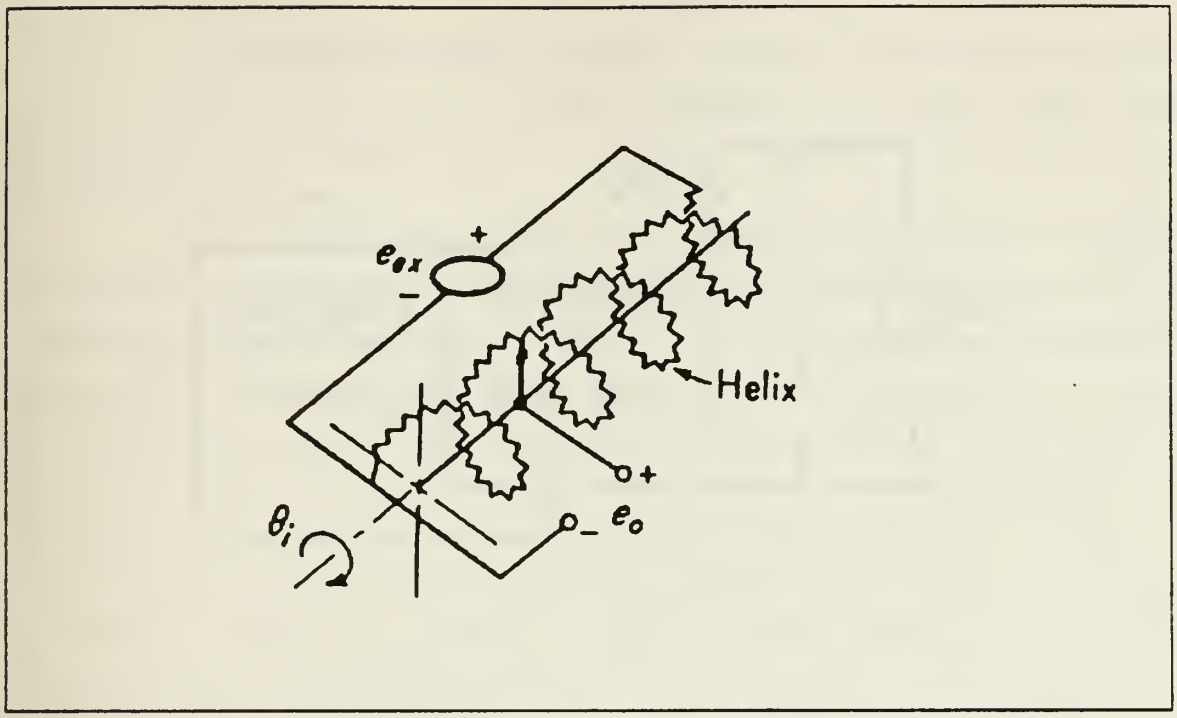


Figure 7. Multiturn Potentiometer: From Ref. 6: p. 218

output. The nonlinear relationship can be seen by analyzing the circuit shown in Figure 8. In the diagram the following variable definitions apply:

- e_X = Input voltage,
- e_o = Output voltage,
- R_p = Total resistance of the potentiometer,
- R_m = Meter resistance,
- x_t = Total range of the potentiometer, and
- x_i = Actual displacement of the potentiometer.

Assuming that R_p is uniformly distributed over x_t, analysis of the voltage divider circuit gives,

$$\frac{e_o}{e_X} = \frac{1}{\frac{x_t}{x_i} + \left(\frac{R_p}{R_m}\right)\left(1 - \frac{x_i}{x_t}\right)} \quad . \tag{3}$$

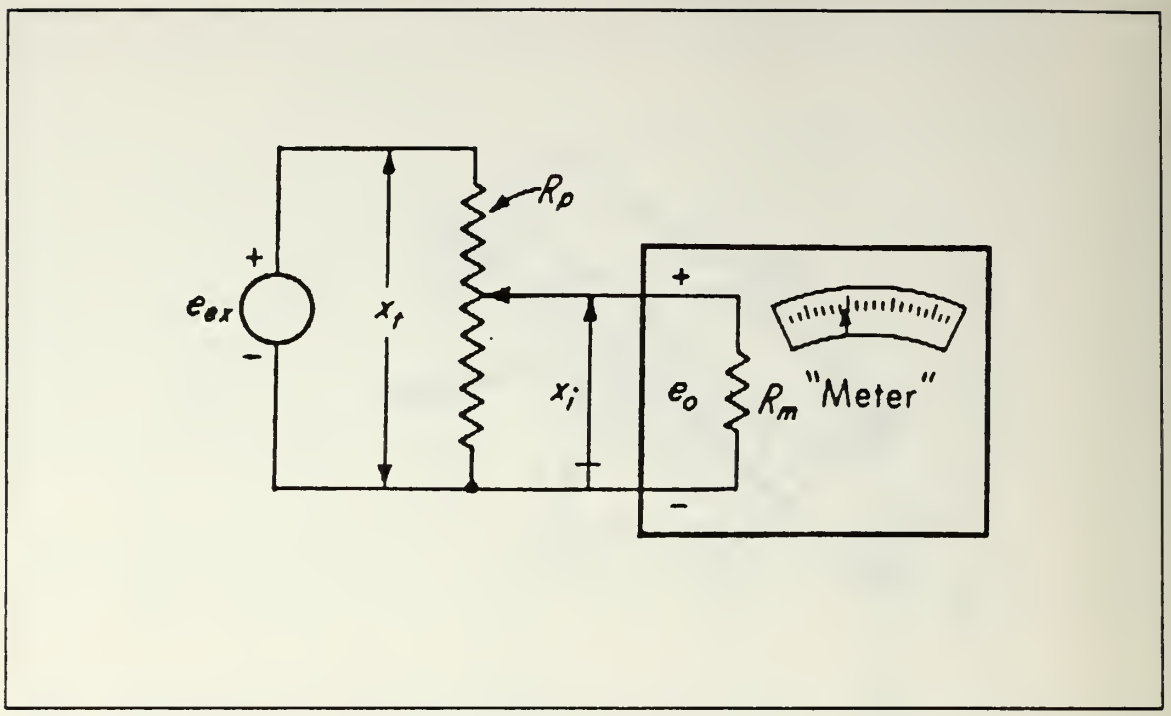


Figure 8. Potentiometric Transducer: From Ref. 6: p. 219

Thus, the ideal (i.e., linear) relationship,

$$\frac{e_o}{e_X} = \frac{x_i}{x_t} \quad , \tag{4}$$

is true only when $R_p / R_m = 0$, and since $R_p \neq 0$, and $R_m \neq \infty$, the nonlinear relationship in (3) will always exist. Doebelin states that "for values of $R_p/R_m < 0.1$ the position of maximum error occurs in the neighborhood of $x_i/x_t = 0.67$, and the maximum error is approximately $15(R_p/R_m)$ percent of full scale." [Ref. 6: p. 218] Other potentiometric transducers, which use a resistive element made of carbon film or a conducting plastic, are not subject to the same kind of resolution limitations as wirewound devices; however, they do have high output impedances and the corresponding nonlinearities described above. [Ref. 6: pp. 217-224]

A high quality multiturn potentiometer used in conjunction with a high quality voltmeter offered one possible solution to the design problem. However, the nonlinearity of this arrangement was a significant disadvantage, and the primary reason why potentiometers were not used.

d. Encoders

The angular displacement transducer, referred to in general as an angular encoder or shaft encoder, converts an angular displacement into a digital signal without the use of an analog-to-digital converter. In today's increasingly digital world this can be a distinct advantage.

There are three different transduction methods used in encoders. Magnetic encoders use a pattern made from magnetized and nonmagnetized segments and one or more magnetic sensors that register as either "1's" or "0's" depending on the magnetic characteristics of the section that they are adjacent to. Brush-type encoders are similar, but the sections are made of conducting and nonconducting materials. The conductors are all tied to a common source and the "sensor" is one or more brushes connected to the output. When the brush is in contact with one of the conductors the output is "on" and when the brush is in contact with an insulator the output is "off". Optical encoders (See Figure 9) use a pattern of opaque sections marked on an otherwise transparent disk. A light emitting diode (LED), or other light source, is placed on one side of the disk, and as the disk rotates a light sensor on the other side of the disk "sees" periods of dark and light which it converts into a digital signal. [Ref. 2: p. 106]

Angular encoders are further categorized as either absolute encoders or incremental encoders. Absolute encoders, similar to the optical encoder shown in Figure 9, use a multitrack pattern on a code wheel to produce a unique coded output signal for each incremental change in the measurand. These wheels use a variety of codes, including binary code, binary-coded decimal (BCD) and Gray code, to determine the shaft position. The resolution of an absolute shaft encoder is limited by the number of tracks on the disk and the type of code used. A simple binary or Gray code encoder, which are more efficient than the BCD encoders, with N tracks has an optimum angular resolution of

$$\Delta\theta = \frac{360^\circ}{2^N} \quad . \tag{5}$$

Thus, to achieve the desired resolution of 10^{-4} radians on the Pan axis with an absolute encoder would require a code wheel with $N \geq 16$. Since the output from the encoder is unique for each position, these devices are not affected by power outages, and the requirements for a signal processor for such a device would be limited to a simple decoding circuit. These encoders can measure angles of up to 360° without ambiguity.

Incremental encoders use a code wheel which has only one track. As the shaft of the incremental encoder rotates the output from the encoder is a series of equally spaced pulses. These pulses can then be used as an input signal to an up/down (U/D) counter of some sort. The output from the counter is an indication of the displacement of the axis from some predetermined reference. The resolution of an incremental encoder is a function of the number of pulses the code wheel generates per revolution and is given by;

$$\Delta\theta = \frac{360^\circ}{n \times PPR} \tag{6}$$

where PPR is the number of pulses per revolution of the code wheel, and n is the number of revolutions that the code wheel makes per revolution of the axis of interest. If the incremental shaft encoder was mounted on the shaft of interest (n = 1) at least 62,832 PPR would be required to ensure a resolution of 10^{-4} radians.

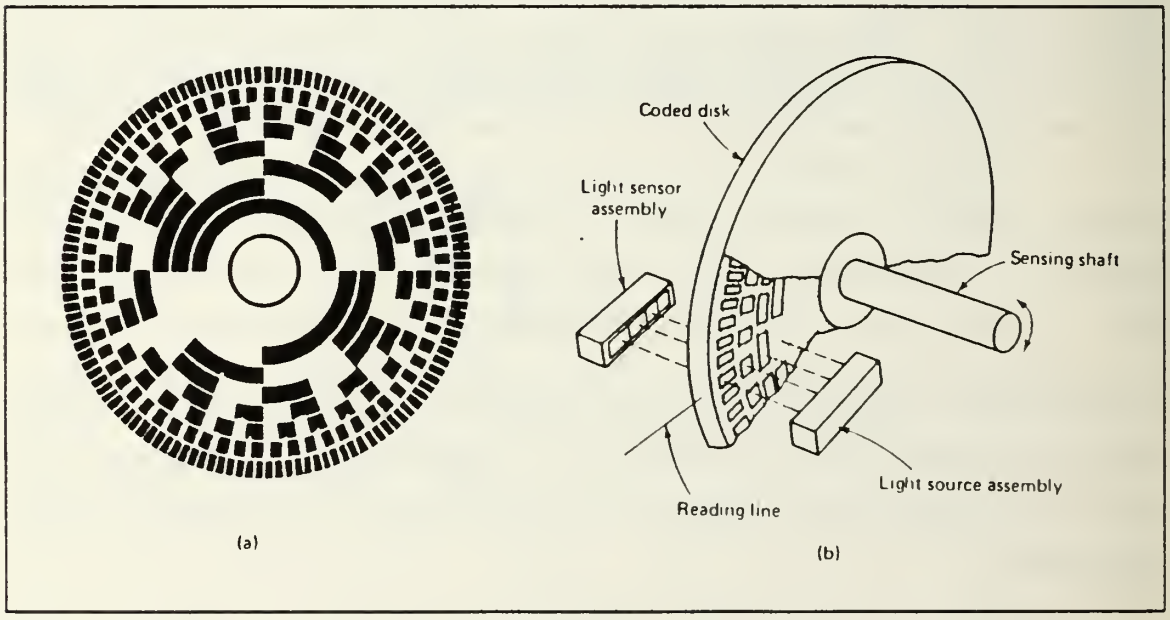


Figure 9. Absolute Photoelectric Angular Encoder: (a) typical code disk; (b) encoder elements. From Ref. 2: p. 107.

Shaft encoders currently range in price from less than $100.00 to several thousand dollars depending on their capabilities and the method of transduction used. Litton Encoder's Model 60 absolute shaft encoder uses a natural binary code, has 15 tracks (0.1917 mrad resolution) and is available "off the shelf" for approximately $3000.

Other absolute encoders with comparable resolutions are available at similar prices. No incremental encoders were found which offered the same kind of resolution as Litton's Model 60; however, because they are not limited to one revolution of the axis, the resolution of an incremental encoder can be improved by a factor of n by causing its code wheel to rotate n times for every rotation of the axis of interest. Incremental encoders with 1024 PPR are available from a variety of manufacturers for about $100 each. Connecting such a device to the axis of interest via a gear train with a 50:1 ratio would theoretically result (from (6)) in a resolution of 0.1227 mrad. Incremental encoders do require more complex signal processing than absolute encoders, and they are affected by power shut-off. Additionally, unlike absolute encoders, any missed or erroneous count that occurs with an incremental encoder will cause a persistent error. [Ref. 7: p. 16]

After considering the measurement system performance criteria and the capabilities and limitations of the various transducers, the use of an incremental, optical shaft encoder appeared to be the best selection for the transducer for each axis. This decision involved balancing the various advantages and disadvantages of the different transducers. The following list gives a summary of the key considerations in this decision.

- Small, lightweight, highly accurate and relatively inexpensive models were readily available. Being small and lightweight suggested that mounting and weatherproofing the transducers in the camera servo should not be too difficult.
- Absolute encoders offer almost all of the advantages of the incremental encoders; they are not affected by power outage, they require less complex signal processing and one time counting errors do not persist. However, these features did not seem to justify the additional price of an absolute encoder.
- Linearity and loading problems associated with the potentiometric displacement transducers were avoided.
- Direct conversion of the measurand into a digital signal precluded the requirement for an A/D converter. (This would have been a disadvantage had the use of an analog signal conditioner been anticipated.)
- Using two identical transducers, each capable of meeting the specifications for the pan axis, would reduce system complexity while still ensuring that the design specifications were met.

C. MOUNTING THE TRANSDUCER

Once the decision to use an incremental optical shaft encoder was made, selection of a specific model remained. Before selection of an actual piece of hardware could be

Table 1. ANGULAR DISPLACEMENT TRANSDUCERS

TRANSDUCER DESIGN	RANGE	RESOLUTION	LINEARITY	OTHER
Reluctive Displacement (RVDT)	0° –360°	Theoretically infinite; Limited by the signal conditioner.	Poor beyond ± 40°	
Reluctive Displacement (Farrand's INDUCTOSYN)	0° –360°	$\pm (4 \times 10^{-4})°$	Good	Large size limits usefulness with the camera measuring system.
Capacitive Displacement	0° –300°	Theoretically infinite; Limited by the signal conditioner.	Good	Temperature sensitive
Potentiometric Displacement	0° –3500°	Device dependent	Device dependent	The trade-off between range resolution and linearity due to the loading effect of the noninfinite impedance of the signal conditioning devices used.
Absolute Encoders	0° –360°	$\frac{360°}{2^N}$	Good	No A D conversion required. Insensitive to power shut-off.
Incremental Encoders	$\pm \infty$	$\frac{360°}{n \times PPR}$	Good	Simple. Requires more signal processing than absolute encoder but is less expensive.

done though, one additional practical consideration had to be made; where and how could a transducer be mounted in or on the servo in order to measure the position of the Pan and Tilt axes?

The physical layout of the camera positioning servo made direct connection of any type of transducer to the axes of interest virtually impossible without major modification of the servo itself. Major modification of the servo would have been expensive, time consuming and outside the scope of this thesis. It was not considered an option in this case. Measurement of the Pan and Tilt axes' displacements was most readily accomplished indirectly. Each axis of the servo is positioned by a separate dc motor via a gear train. By mounting the shaft encoder code wheels to the sprockets (items 42 and 43 in

Figure 10) which are each attached to one of the worms, an indirect measurement of the position of each of the wormgears (items 5 and 7 in Figure 10) was possible. This approach, made necessary by the servo design, was a mixed blessing.

The backlash in a worm-wormgear connection will cause the position of the worm to be different for any given wormgear position, depending on whether that position is approached from a clockwise or a counterclockwise direction. In order to correctly determine the displacement of the wormgear by measuring the displacement of the worm, the amount of backlash present must be known (i.e., would have to be determined experimentally) and accounted for by the measurement system. This nonlinear source of error would not have been a concern if the servo was only required to rotate in one direction. This was not the case, however, and hysteresis eventually was determined to be the largest single source of error in the measurement system. A more complete discussion of this topic is included in Chapter IV of this thesis.

Assuming for the moment that the effects of the backlash in the gears could have been completely compensated for, mounting the shaft encoders on the worm provided a measurement advantage analogous to the mechanical advantage afforded by the gear train. Initial measurements indicated that each of the worms turned through 18,000° ($50 \times 360°$) for every 360° rotation of the corresponding wormgear. This meant that a shaft encoder with 100 divisions per 360° attached to the worm axis could do the same job as a 5,000 division per 360° encoder attached to the wormgear axis.

D. SELECTING AN OPTICAL SHAFT ENCODER

Once the basic decisions to use incremental optical shaft encoders and to mount the encoders on the worms inside the servo housing had been made, selection of the specific pieces of hardware was relatively straight forward and was primarily a matter of convenience and expediency.

Returning to the design specifications for a moment; the most stringent requirement was to be able to measure the position of the pan axis to within $\pm (5.73 \times 10^{-3})°$. To determine the required resolution for the optical shaft encoder, the following calculations were performed.

First,

$$\frac{360°/\text{Revolution}}{5.73 \times 10^{-3}°/\text{Division}} \simeq 62{,}827 \frac{\text{Divisions}}{\text{Revolution}} \quad . \tag{7}$$

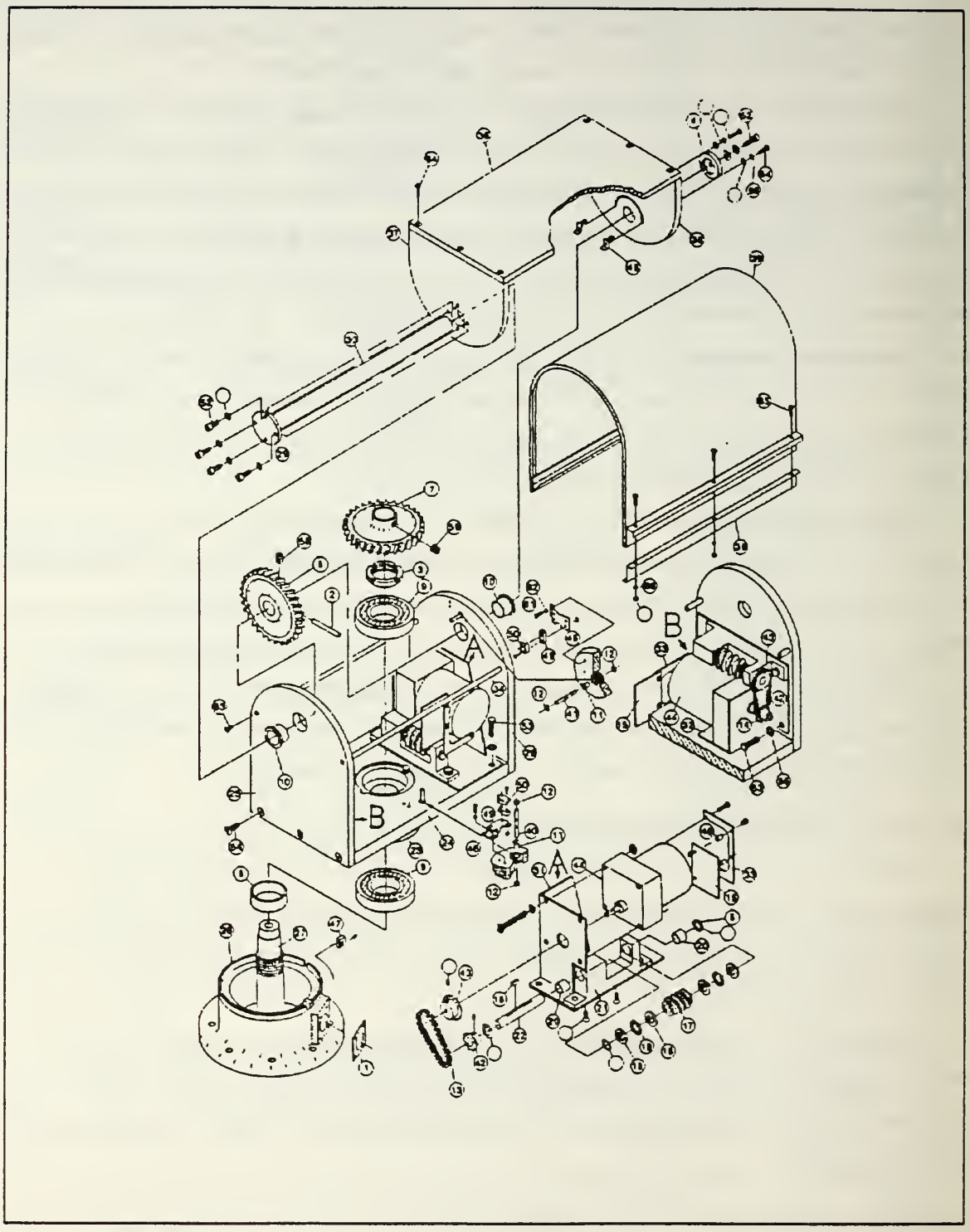


Figure 10. Camera Servo: From Ref. 8: p. 12.

Then, considering the 50:1 gear advantage,

$$\frac{62,827}{50} \simeq 1257 \frac{\text{Divisions}}{\text{Revolution}} \quad . \tag{8}$$

The task therefore was to find an optical shaft encoder capable of detecting bidirectional rotation with at least 1257 Divisions/Revolution in a package small enough to mount in the servo housing on the worm axis. There was no absolute size limitation; however, due to the construction of the servo it was desirable to find an encoder that was no more than 3 in. in diameter and no more than 1.5 in. in width. The companies that make shaft encoders are capable of custom building devices to meet a customer's specific needs. However, the prices are high, and the lead times are long for these special order parts. The encoder for this system needed to be reasonably priced and readily available to ensure timely completion of the project and to facilitate replacement, if necessary, in the future.

Optical shaft encoders are manufactured by numerous companies including Litton, Honeywell, BEI, IVO and Hewlett Packard. Sales literature from these companies was reviewed prior to making a decision on the specific shaft encoder model to be used. Incremental optical shaft encoders with resolutions that range from one pulse per revolution (PPR) to 2540 PPR are available off the shelf from one or more of these companies. While evaluating sources of supply, incremental optical shaft encoders were also found in use in various laboratories and shops in the Electrical Engineering and Physics Departments at the NPS. Encoders immediately available from stock included two Vernitech 1200 PPR (model VOE-23-1200-AI-LD5-2L1-1603-2) encoders from the Physics Department and two Hewlett Packard (HEDS-6000,J06) encoders from the Electrical Engineering Department. The use of the Vernitech encoders was ruled out because they were unable to detect bidirectional movement without increasing the complexity of the signal conditioning subsystem. Additionally, technical literature requested on two separate occasions from Vernitech was never received.

The HEDS-6000,J06 encoders have a resolution of 1024 PPR. Each encoder provides displacement information in the form of TTL logic level signals via two output channels. When the encoder is properly adjusted the two output signals have a 90° phase difference. This quadrature phase relationship permits these encoders to detect bidirectional displacements. Rotation in one direction will cause Channel A to lead

Channel B (in phase), while rotation in the other direction will cause Channel B to lead Channel A. [Ref. 9: p. 2]

The presence of two output channels in quadrature phase has an additional benefit that is useful in some applications. Since the amount of position information has essentially been doubled, if the signal conditioner is designed to detect both the leading and trailing edges of one of the output channels the resolution of the measurement system can be doubled. The difficulty with using this technique is that multiple oscillations about a single point cannot be detected as such. If the camera were to oscillate less than one half of a pulse width about a transition the signal conditioner would detect and erroneously count the multiple transitions. [Ref. 7: pp. 13-16]

With 1024 PPR, which is less than the 1257 PPR required to meet the 0.1 milliradian accuracy specification on the pan axis, the maximum resolution available, if the HEDS-6000 was attached to the worm, can be calculated as;

$$\frac{360^\circ}{(50 \times 1024)} = (7.03125 \times 10^{-3})^\circ \text{ Pulse}^{-1} \quad . \tag{9}$$

Although this was not sufficient to satisfy the pan axis resolution specification of $(5.73 \times 10^{-3})^\circ \text{Pulse},^{-1}$ all of the other performance criteria could be satisfied. The trade-off seemed reasonable and was approved prior to proceeding further with the system design.

E. THE DISPLAY

Selecting a method to display the final system output was certainly the least demanding task required in the design of the system. With an expected resolution on the pan axis of approximately 0.007° over a range of 360° (a ratio of about 1:51,500) an analog display seemed out of the question. A five or six digit digital display on the other hand offered a simple, reliable and cost efficient means of presenting the output. Constructing the displays from individual, seven-segment, common anode, LED devices, and the appropriate display drivers was a straight forward task.

F. THE SIGNAL CONDITIONER

Anticipating the use of two incremental shaft encoders as the transducers for the measurement system and the use of digital readouts as the display devices significantly reduced the number of possibilities for the signal conditioning subsystem. In addition to the hardware and software described in each of the subsequent discussions, each

technique listed here would require an edge detector to detect the transitions in the TTL signals from the shaft encoders.

- Up/down counter with table look-up.
- Up/down counter and multiplication.
- Add/subtract.
- Microcomputer.
- Microprocessor.

1. Up/down (U/D) counter with table look-up

This technique would involve the use of a shift register, some associated logic, an U/D counter and a table look-up device such as an erasable programmable read only memory (EPROM). The shift register would serve as a hardware buffer that could be used to account for the hysteresis introduced by the worm-wormgear assembly. The length of the buffer would have to be determined experimentally. The logic associated with the shift register would determine the "validity" of each transition (count) signal from the edge detector by checking the contents of the shift register and comparing the current direction of rotation with the previous direction of rotation. Whenever the logic detected a change in rotation direction, or a partially full, or a partially empty buffer (depending on the direction of rotation), the transition would not represent a "valid" count since any of these conditions would indicate that the transition was due to a change in the position of the worm without a corresponding change in the position of the wormgear. Thus, the present transition would be the result of hysteresis due to the backlash in the gear train and the transition would be "invalid". Such a transition would cause the contents of the hysteresis buffer to be modified appropriately. A more complete discussion of this topic is contained in Chapter IV. The shift register and associated logic could be built from common TTL devices readily available at the NPS.

Once a count had been determined to be valid, an U/D counter would be used to keep a running total of the number of counts. Again, such a device could be built using readily available TTL devices such as the 74LS168A, Synchronous 4-Bit Up/Down Decade Counter, or the 74LS169A, Synchronous 4-Bit Up/Down Binary Counter. The output from the U/D counter would then be used as an address to "look up" a predetermined number stored in an EPROM.

This design approach was considered relatively straightforward, and at least initially seemed like a viable option. Its major advantage was that it was conceptually quite simple. This simplicity had a price though; it would have been very hardware in-

tensive and consequently would have been a very inflexible design. For example, if at a later date the use of an arbitrary reference was desired, additional hardware would have to be added to the signal conditioner so that the counter could be initialized to the arbitrary starting point. Since all of the processing would have to be done in hardware, even a minor modification in the system could necessitate a major design revision. Another consideration was that saving in excess of 51,000 unique positions in the EPROM presented a nontrivial problem that would need to be solved if this technique was used.

2. Up/down counter and multiplication

This is very similar to the previous case, differing only in that instead of looking up a predetermined position, in a memory device, a multiplier would be used to multiply the output of the U/D counter by a predetermined constant. As an example, if experimental results indicated that the shaft encoders generated one pulse for every 0.00703125° that the camera was displaced, then each time a valid count was received, the updated count would need to be multiplied by 0.00703125 in the final stage of the signal processor. The result would be the new position. Again, while conceptually simple this idea had some significant disadvantages. Even more hardware intensive than the first approach, this design would also have extremely limited flexibility.

Accomplishing the multiplication would have posed a formidable task. The scale factor would have to be written as some integer (e.g., 0.00703125 would become 703125, or 70323, or 7031, etc.) depending on the desired accuracy. The count, already an integer, would be multiplied by the constant and the correct position of the decimal point would have to be determined. Locating the decimal point would be a relatively simple task, but multiplication of two numbers such as 51,000 and 70,313 would not be as easy. At least one 16 bit by 16 bit binary multiplier (i.e., TRW's MPY016H) is currently available, but since the number 70313 cannot be represented in binary by less than 17 bits, the multiplication could have been accomplished in either of two ways. One solution would have been to perform the multiplication in two or more stages. Alternatively, 70313 could be "rounded" to 7031. The second option would create a cumulative round-off of about $(1.28 \times 10^{-3})°$ per 360° rotation (assuming 51,200 pulses per 360°). This round-off error would probably have been acceptable, but the complexity and limited flexibility of either multiplication scheme made the U/D counter and multiplication an unacceptable candidate for the signal processing subsystem.

3. Add/subtract

A third design concept considered the elimination of the U/D counter altogether. The same logic proposed for use in the previous two designs could have been

used to check the validity of a count and to determine the direction of rotation. However, instead of valid counts being sent to an U/D counter as before, these counts would now signal an adder to add or subtract a predetermined constant from the running total. Just as before, this simple idea could probably have been made to work at least once, but its usefulness as a part of a larger system would certainly have been limited. The large number of components required to realize this design would have increased the probability of failure, complicated troubleshooting and reduced overall flexibility.

4. Microcomputer

If the signal processing subsystem was built around a microcomputer (PC), virtually all of the disadvantages associated with the previously discussed approaches would be eliminated. Since all of the logic could be implemented in software, modifications to the system would be relatively simple to make, and the system's flexibility would be enhanced. However, dedicating a microcomputer, even an inexpensive model, to the signal processing tasks for this measurement system was considered overkill, and timesharing with one of the PC's already in service was possible, but not considered practical or convenient since these microcomputers had already been dedicated to a variety of tasks.

5. Microprocessor

One final option for the signal processor remained. Microprocessors are relatively inexpensive and powerful and are available in a wide variety of makes and models. If a microprocessor was used instead of a microcomputer or a straight hardware processor, the "nice to have" requirements such as flexibility, ease of modification and capacity for expansion, as well as the required signal processing functions could all be satisfied. On the other hand, microprocessors have one distinct disadvantage; they are not user friendly. The use of a microprocessor implied countless hours spent tracking individual bits, debugging assembly language code, studying timing diagrams, etc.. No matter how distasteful the thought, however, a microprocessor was clearly the best way to perform the signal processing functions of the measurement system.

As with the selection of the transducer, once the basic design approach had been determined, selection of a specific device was a relatively straight forward task. The choice of one microprocessor over another was a function of the processor's ability to perform the required tasks, cost effectiveness and availability. Motorola's MC68705U3 seemed to satisfy all of these requirements. The MC68705U3 is a four kilobyte EPROM microprocessor, built using HMOS (high-density NMOS) technology with an eight bit architecture. The "68705" operates on a 5.0 volt dc supply, has 112 bytes of on chip RAM, four vectored interrupts, 24 TTL/CMOS compatible bidirectional I/O lines (eight

lines are LED compatible), eight dedicated input lines and an internal eight bit timer with a seven bit programmable prescaler. [Ref. 10: p. 1]

In Ref. 10 Motorola advertises the following software features:

- Programming language similar to the 6800 family.
- Byte efficient instruction set.
- Easy to program.
- True bit manipulation.
- Bit test and branch instructions.
- Versatile interrupt handling.
- Powerful indexed addressing for tables.
- Versatile index register.
- A full set of conditional branches.
- Memory usable as registers/flags.
- Single instruction memory examine/change capability.
- Ten powerful addressing modes.
- All addressing modes apply to EPROM, RAM and I/O.

One key advantage to using the MC68705U3 was that one of the microprocessors, and a Motorola M68705EVM (the evaluation/programming module for the M6805 family of devices) were both available for immediate use at the NPS. The fact that the 68705 utilized HMOS technology suggested that it should be a relatively low cost microprocessor. In fact, except for the price of a phone call, a second microprocessor was obtained free of charge from a local electronics wholesaler. Additional microprocessors, to be used as replacements and as backup devices were ordered for about $20.00 each.

One potential problem with using a microprocessor begged checking prior to proceeding. Initial measurements of the camera's maximum rotation velocity produced the following results.

$$\omega_{PAN\,(\max)} \simeq 1.0 \text{ rpm} \tag{10}$$

$$\omega_{TILT\,(\max)} \simeq 0.5 \text{ rpm} \tag{11}$$

Again the requirements for the pan axis presented the most stringent design limitations. Since the optical shaft encoders were anticipated to deliver 51,200 PPR (1024×50) the

microprocessor on the pan axis had to be capable of processing 51,200 pulses/minute (1.172 ms / pulse). The MC68705U3 is designed to operate with an oscillator frequency (f_{osc}) of between 0.4 MHz and 4.4 MHz and has an instruction cycle time ($4/f_{osc}$) of between 0.950 μs and 10 μs. Assuming that a 4.0 MHz clock was used, the instruction cycle time would be 1.0 μs. This would mean that the processing of each pulse would have to be accomplished in no more than 1172 instruction cycles to ensure that no pulses would be missed.

III. DESIGN

A. GENERAL

The schematic diagrams for the measurement system are shown in Appendix A; Appendix B contains copies of the printed circuit board plans. Before describing the detailed operation of each of the individual components of the measurement system, a brief overview of its basic theory of operation is in order. The measurement system is actually two separate systems operating independently. The system designed to measure the azimuth or pan angle will subsequently be referred to as the "Pan System", and the other system, designed to measure the elevation or tilt angle, will be referred to as the "Tilt System". However, because the two systems are quite similar the discussion which follows will only specifically describe the operation of both systems where their operation differs.

In the most general terms, the measurement system shown in Figure 2 on page 6 uses two microprocessors to count the pulses generated by the incremental shaft encoders, and to provide output signals to the display devices. The counting function performed by each microprocessor involves determining the direction of rotation and determining whether each count is "valid". Valid counts are encoder pulses which result from the displacement of the camera servo, while invalid counts are a result of the hysteresis in the gear train. The number of valid counts is directly proportional to the angular displacement of the camera axis.

Both of the displays are capable of presenting the position information in two basic forms. In the Count Mode they display the number of pulses that have been detected, and in the Position Mode they display the angle in degrees that the number of pulses represents. A third display mode, which is a combination of the first two, is also available. In the third mode, referred to as the "Blinking Mode", the display will alternately display the count and the angle.

B. SHAFT ENCODER AND LINE DRIVER

Figure 11 shows the basic components of the HEDS-6000 incremental optical shaft encoder. The encoder is approximately 56 mm in diameter and 20 mm deep. The code wheel assemblies for the HEDS-6000 J06 encoders are designed to mount on 0.25 in. shafts. Since the mounting surface shown in Figure 11 is not part of the encoder kit, and did not existed on either of the worm axes, two such surfaces were machined in the

Physics Department Shop and attached to one end of each of the worms. Each surface has a 0.25 in. diameter shaft to which one of the code wheel assemblies is attached. Two sheet metal brackets, also made in the Physics Department Shop, are bolted to the servo frame. The encoder bodies are mounted to these brackets. Figure 12 shows the shaft encoders mounted in the camera servo. [Ref. 9: p.1]

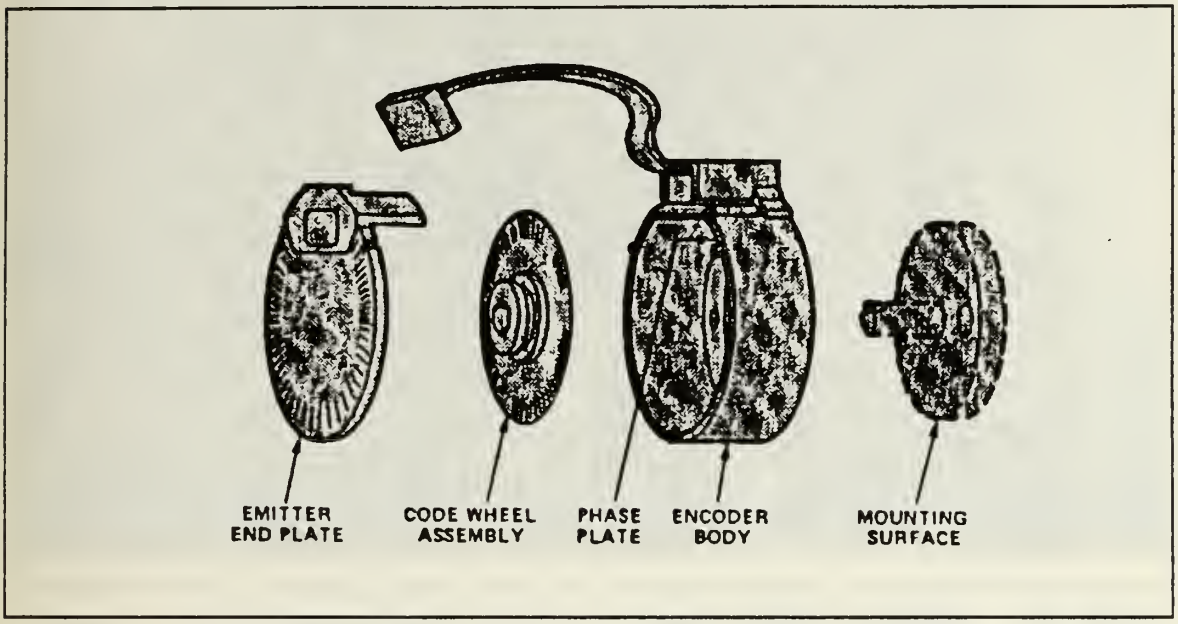


Figure 11. HEDS-6000 Series Encoder Kit: From Ref 9: p.6.

Also seen in Figure 12 is a printed circuit board mounted between the two optical shaft encoders. Each of the encoders is electrically connected to the board via a separate ten wire ribbon cable. The power and the output signals from the shaft encoders are transmitted through these cables. A sketch of the ribbon cable connector and the pinout for the connector are shown in Figure 13. Each connector is attached to a ten pin header on the printed circuit board. Pins 2, 7 and 9 are connected to a +5.0 Vdc power supply external to the camera servo. A description of the power supply is given later in this chapter. Pins 3, 4, 5 and 6 are connected to the power supply ground. The HEDS-6000 does not have an index pulse, therefore pin 10 is not connected.

The remaining two pins on each header connect the output channels of the shaft encoders to two 74S140 line drivers. Each 74S140 is a dual four-input NAND gate 50-Ohm line driver. The line drivers are powered by the same supply as the encoders. They serve as buffers between the encoders and the transmission lines which are used to transmit the encoder signals to the signal conditioner. The line drivers' typical high

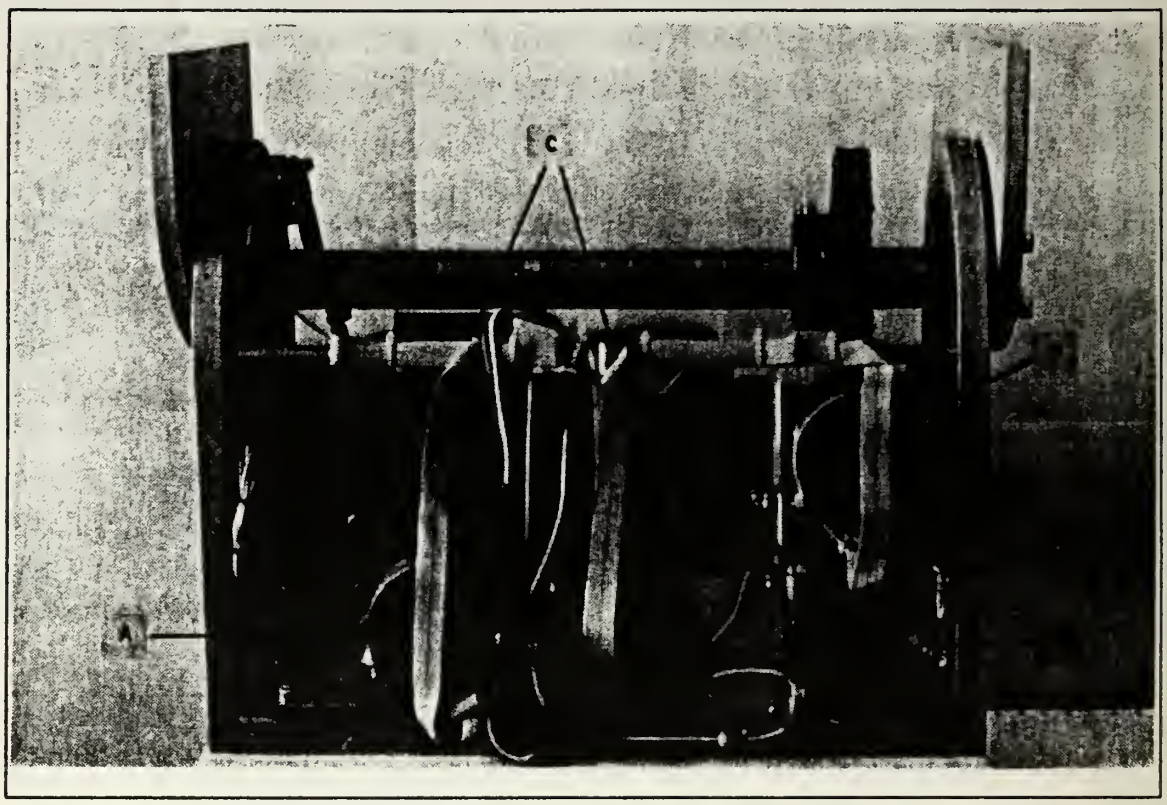


Figure 12. Modified Camera Servo: (a) Optical shaft encoder used to measure Pan axis displacement, (b) Optical shaft encoder used to measure Tilt axis displacement, (c) Ribbon cable, (d) Printed circuit board.

output current is 10 mA and the maximum is 18 mA. Resistance in the transmission line was measured to be approximately 35 Ω, and to be on the safe side a 10 Ω connector loss was assumed. The voltage drop due to an 18 mA current through a 45 Ω resistance is 0.81 V. A "voltage high" signal received at the signal conditioner should therefore be about 4.19 V. This is well above the maximum, positive-going threshold voltage specification of 2.0 V for the 7414 Schmitt triggers, which are used to receive the signals at the signal processor. [Ref. 11: pp. 5-73, 5-74, 6-44]

C. ENCODER-MICROPROCESSOR INTERFACE

The signals transmitted by the two line drivers are Channels A and B of each of the shaft encoders. These signals contain the raw data which the signal processor converts into position information. Three pairs of multiple pin connectors are used in the encoder-microprocessor interface. The pinouts for these connectors are shown in

BOTTOM VIEW

PINOUT

PIN #	FUNCTION
1	CHANNEL A
2	V_{CC}
3	GROUND
4	N.C. OR GROUND
5	N.C. OR GROUND
6	GROUND
7	V_{CC}
8	CHANNEL B
9	V_{CC}
10	CHANNEL I

Figure 13. Encoder Connector Specifications: From Ref. 9: p. 6.

Figure 14. Each of the four signals is received at the signal processor by a 7414 Schmitt trigger which is used to "clean up" the signal. The Schmitt triggers lower the system's susceptibility to errors caused by slow state transitions and increase the signals' fan out capabilities [Ref. 7: p. 13].

The output of each Schmitt trigger is routed to an input port of the appropriate microprocessor. Each Channel A signal is also the input to an edge detector. The edge detectors each consist of three 7414 inverters, a 74LS86 EXOR gate and a 47 nF capacitor, configured in the manner shown in Figure 15. This configuration causes the interrupt line to go low for approximately 2 μs each time Channel A transitions from low to high or from high to low. Since an oscillator frequency, f_{osc}, of 4.0 MHz is being used, the interrupt pulse width, t_{WL}, must be greater than or equal to 1.25 μs [Ref. 10: p. 3]. The value of the capacitor required to achieve the 2 μs delay was determined experimentally.

D. SWITCHES

The measurement system has 10 switches that allow the operator to control specific functions of the signal processors and the displays. Figure 16 shows the physical location of these switches on the control panel. Switches SW1(P) and SW1(T) control the reset lines to the microprocessors. Switches SW2(P), SW2(T) and SW5 control the display mode. The Function and Set switches; (SW3(P), SW3(T), SW4(P) and SW4(T)) allow the user to change the length of the hysteresis buffer in the microprocessor. The

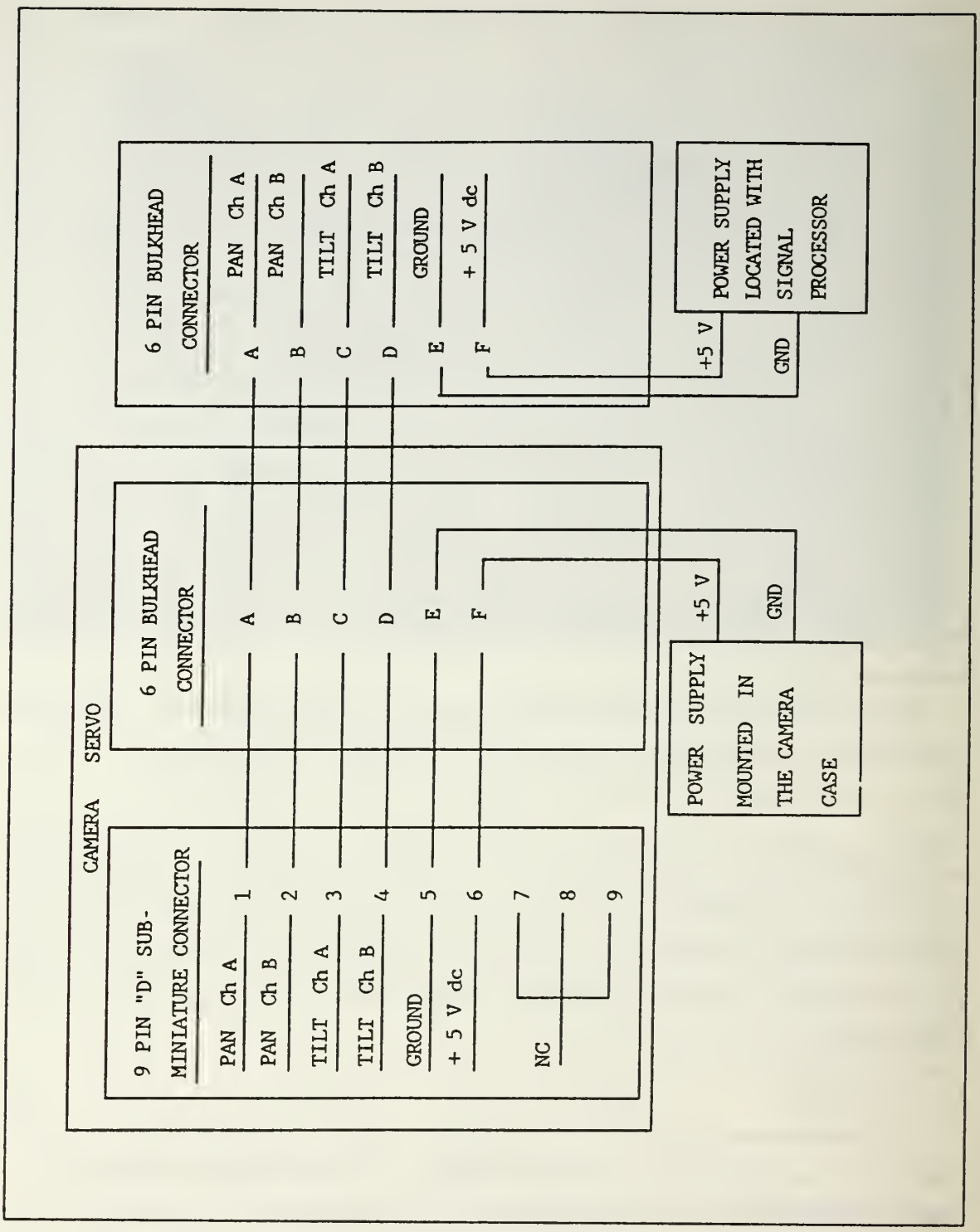


Figure 14. Encoder-Microprocessor Connector Specifications

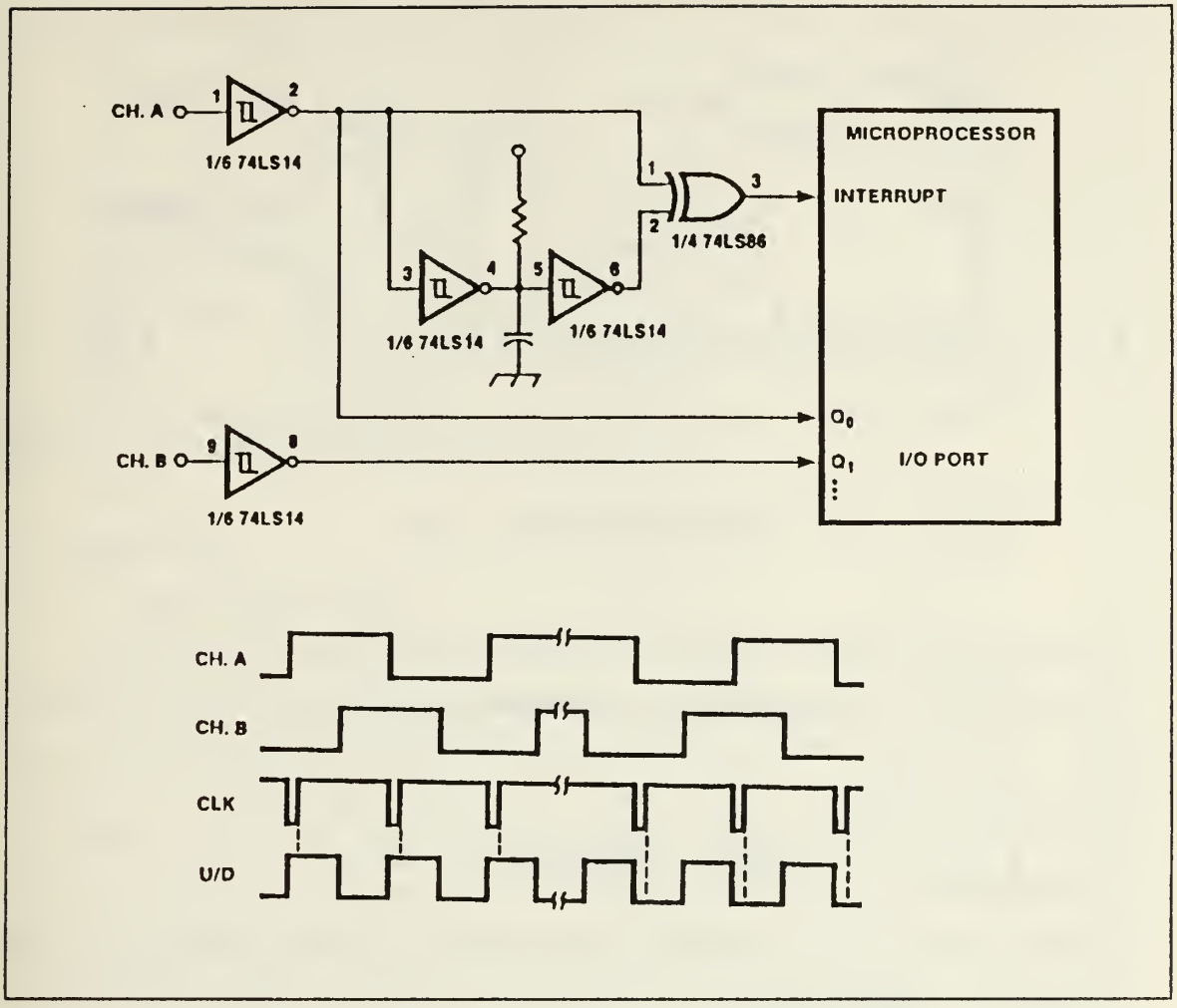


Figure 15. Interrupt Interface: After Ref 7: p. 14.

master power switch is SW6. Table 2 identifies the switches by name, description and function.

Any mechanical switch will "bounce" or "chatter" when it is thrown, and since the operation of the signal processor depends on the number of times that the Display Mode and Set switches change position, these switches had to be "debounced". A very simple but effective way to do this is with an $\overline{RS}$ latch. Switches SW2(P), SW2(T), SW4(P) and SW4(T) are each debounced in this manner. Each latch is made from two 74S00 NAND gates connected in the manner shown in Figure 17. [Refs. 13: pp. 132-135, 12 : pp. 3,4]

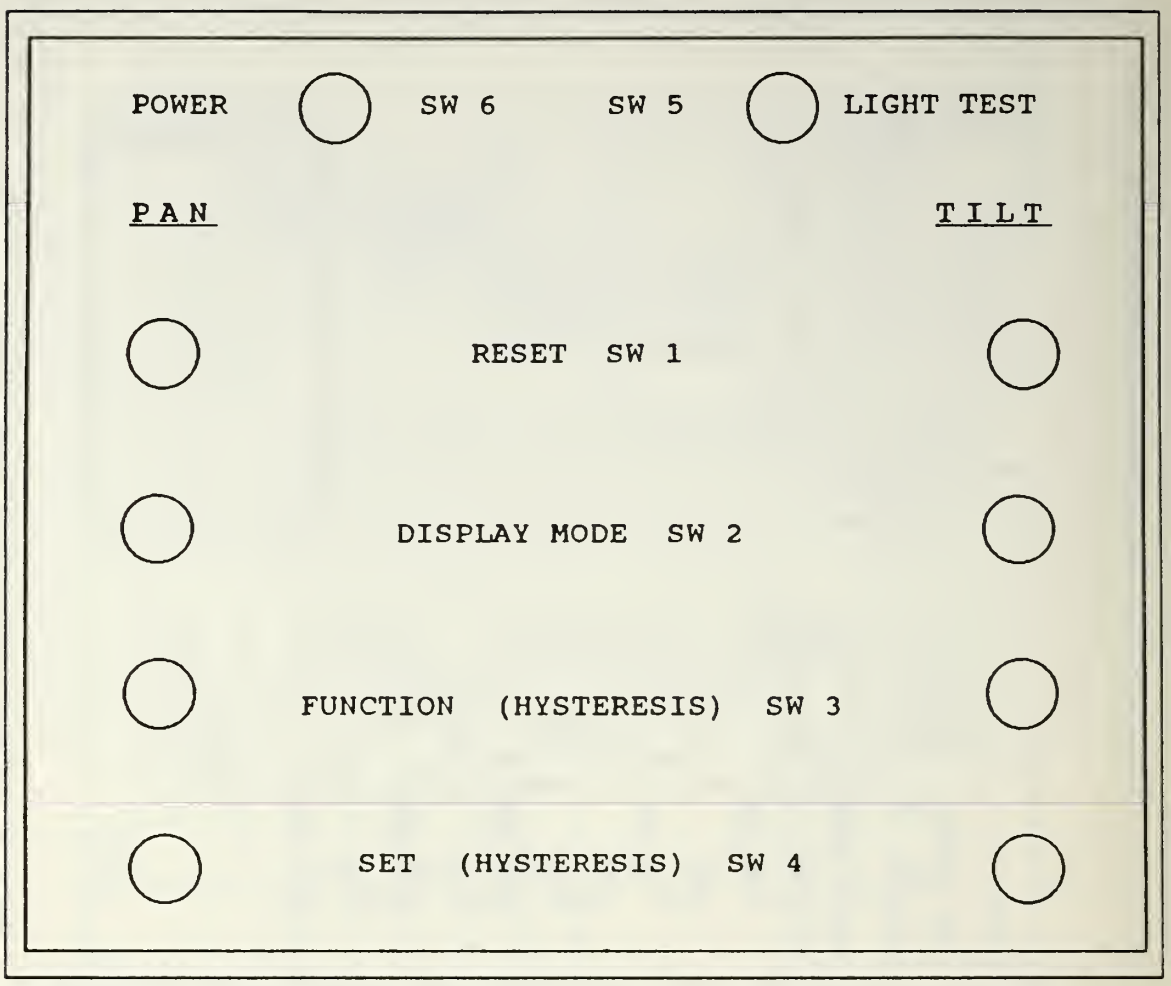


Figure 16. Control Panel

E. MC68705U3

1. General

The two 40 pin MC68705U3 microprocessors (MPU's) are the heart of the measurement system. With the exception of the light test signal, every signal in the system is either part of the input to one of the MPU's or part of their output. The MPU's were programmed using the assembly language syntax, assembler directives and instruction set for the M6805 family of microprocessors which are described in Ref. 14. The Pan and Tilt programs are listed and their operation is described in Appendix D. The pin assignments for the MC68705U3 are shown in Figure 18. Table 3 briefly describes the purpose of each pin and the actual connections for the two MPU's.

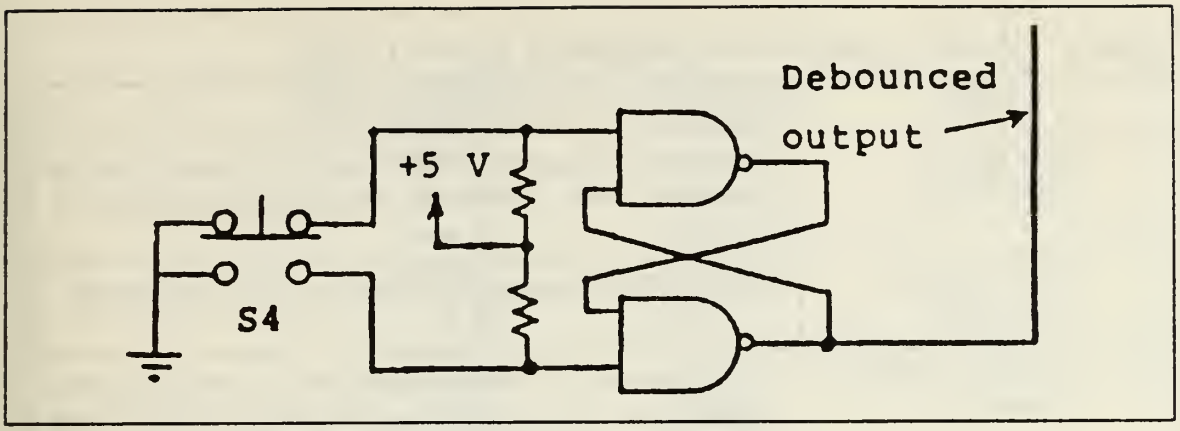


Figure 17. Debouncing circuit: After Ref 12: p. 4.

2. **Memory Map**

a. Input/Output (I/O)

The memory map for the MC68705U3 is shown in Figure 19. The digits following a "S" are the hexadecimal representation of the address for a specific memory location. The data registers occupy the first four memory locations of each MPU. Thus the information written into the registers at S000, S001 and S002 is written to the output ports A, B and C respectively. Port D, at address S003, is an input only port as indicated in Table 3. In order to determine the state of the input lines, the contents of the register at S003 must be read by the MPU. Registers S004, S005 and S006 are the data direction registers (DDR's) for Ports A, B and C respectively. Because all three ports are used as "output only" ports, in this application, the DDR's are all established as such by an initialization routine performed by the MPU's during their initial power-up and after each external reset. [Ref. 10: pp. 5, 12, 14]

Pin 18 of the MPU can be used as either a general purpose input line or as an interrupt line. The primary interrupt line on each MPU is used to signal the occurrence of a state transition on Channel A. Pin 18 is used as a second interrupt line to signal a display mode change request from the operator. The Miscellaneous Register (MR) at address S0A is used to control the operation of the second interrupt line ($\overline{INT2}$). In order to establish pin 18 as an interrupt line, bit 6 of the MR is cleared by the Initialization Routine. The $\overline{INT2}$ Interrupt Request Bit, bit 7 of the MR, is cleared by default upon reset. It is set when a falling edge is detected on the Display Mode line which is connected to pin 18. When this occurs and bit 6 of the MR is cleared, an interrupt request is generated. This interrupt request causes the display mode to change.

Table 2. SIGNAL PROCESSOR AND DISPLAY SWITCHES

NAME	DESCRIPTION AND FUNCTION
PAN RESET (SW1(P))	Momentary action push button switch: Resets the Pan Microprocessor. Causes the Pan Display to be reset to zero.
TILT RESET (SW1(T))	Same as SW1(P) except it affects the Tilt System only.
PAN DISPLAY MODE (SW2(P))	Single pole double throw toggle switch: Each time the switch position is changed the Pan Display toggles from Count mode, to Position Mode, to Blinking Mode, to Count Mode, etc..
TILT DISPLAY MODE (SW2(T))	Same as SW2(P) except it affects the Tilt Display only.
FUNCTION (HYSTERESIS) (SW3(P))	Single pole double throw switch: When closed, causes the "Function" line of the Pan Microprocessor to go low and causes the size of the hysteresis buffer to be displayed on the Pan Display. Enables SW4(P).
FUNCTION (HYSTERESIS) (SW3(T))	Same as SW3(P) except it affects the Tilt System only.
SET HYSTERESIS (SW4(P))	Single pole double throw switch: Inoperable unless SW3(P) is closed. If SW3(P) is closed, each time the position of SW4(P) is changed the length of the hysteresis buffer is incremented by one. Maximum buffer length is 25. Toggling SW4(P) when the buffer length is 25 will cause the buffer length to be reset to zero.
SET HYSTERESIS (SW4(T))	Same as SW4(P) except it affects the Tilt Hysteresis buffer.
LIGHT TEST (SW5)	Single pole single throw switch: When closed, lines 1, 2, 7, 8, 10, 11 and 13 on each of the LED displays will go low. Unless an element is burned out, every digit in both displays should be an eight.
POWER (SW6)	Single pole single throw switch: When closed, applies +5.0 V dc power to the signal processors and the displays.

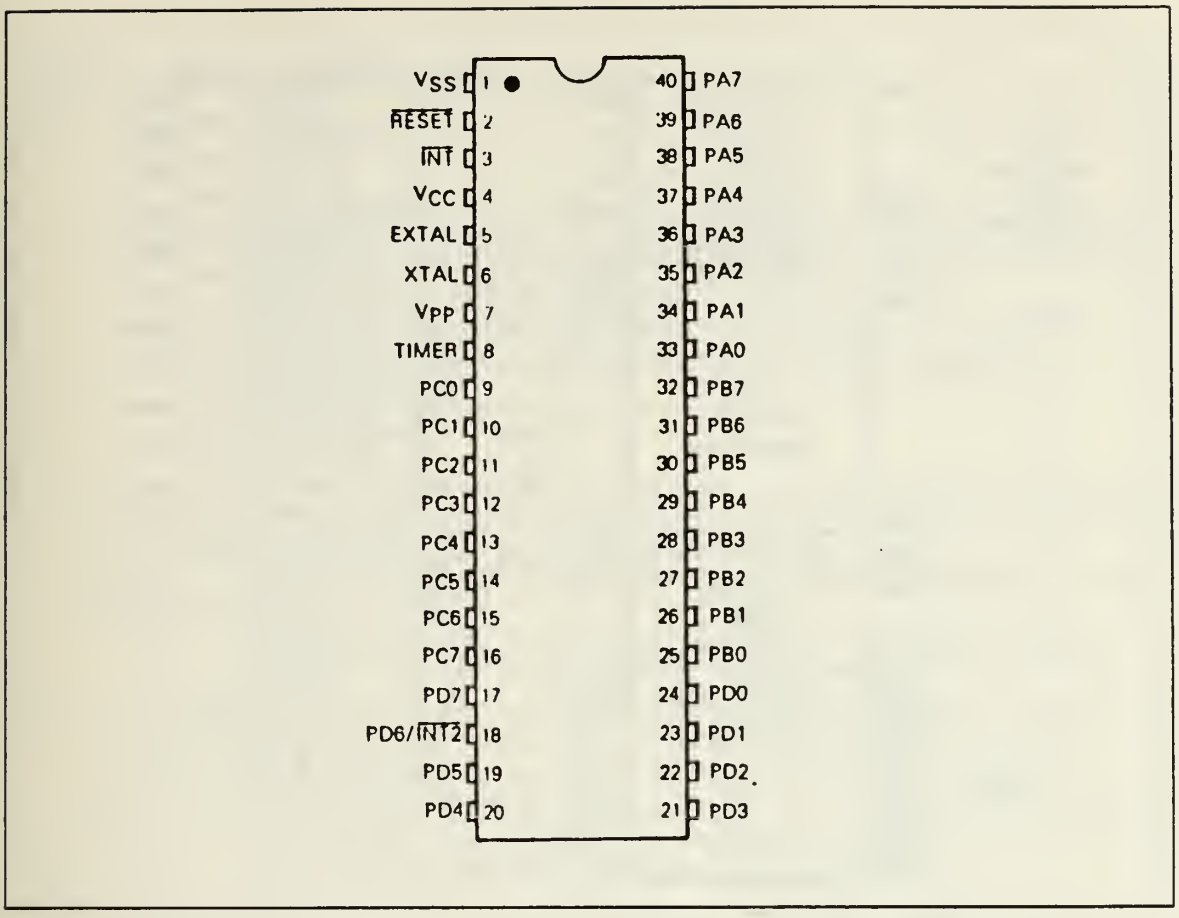


Figure 18. MC68705U3 Pin assignments: From Ref. 10: p. 1.

Once bit 7 has been set by an interrupt, it must be cleared by software to avoid repeated and unwanted interrupts from occurring. This task is performed by the Mode Change Routine in each EPROM. [Ref. 10: pp. 1, 10, 13, 15]

b. Timer

The operator can cause either or both of the displays to "blink" by using the Display Mode Switches, SW2(P) and SW2(T). When one of the systems has its display in the Blinking Mode, the associated MPU uses its timer to generate a timer interrupt request every second. The interrupt request causes the MPU to execute the Mode Change Routine. A block diagram of the timer is shown in Figure 20. The timer consists of an eight-bit counter which is decremented toward zero by the f_{CIN} input. When the counter reaches zero, it sets the Timer Interrupt Request Bit (TIR) of the Timer Control Register (TCR), and a timer interrupt request is generated unless the

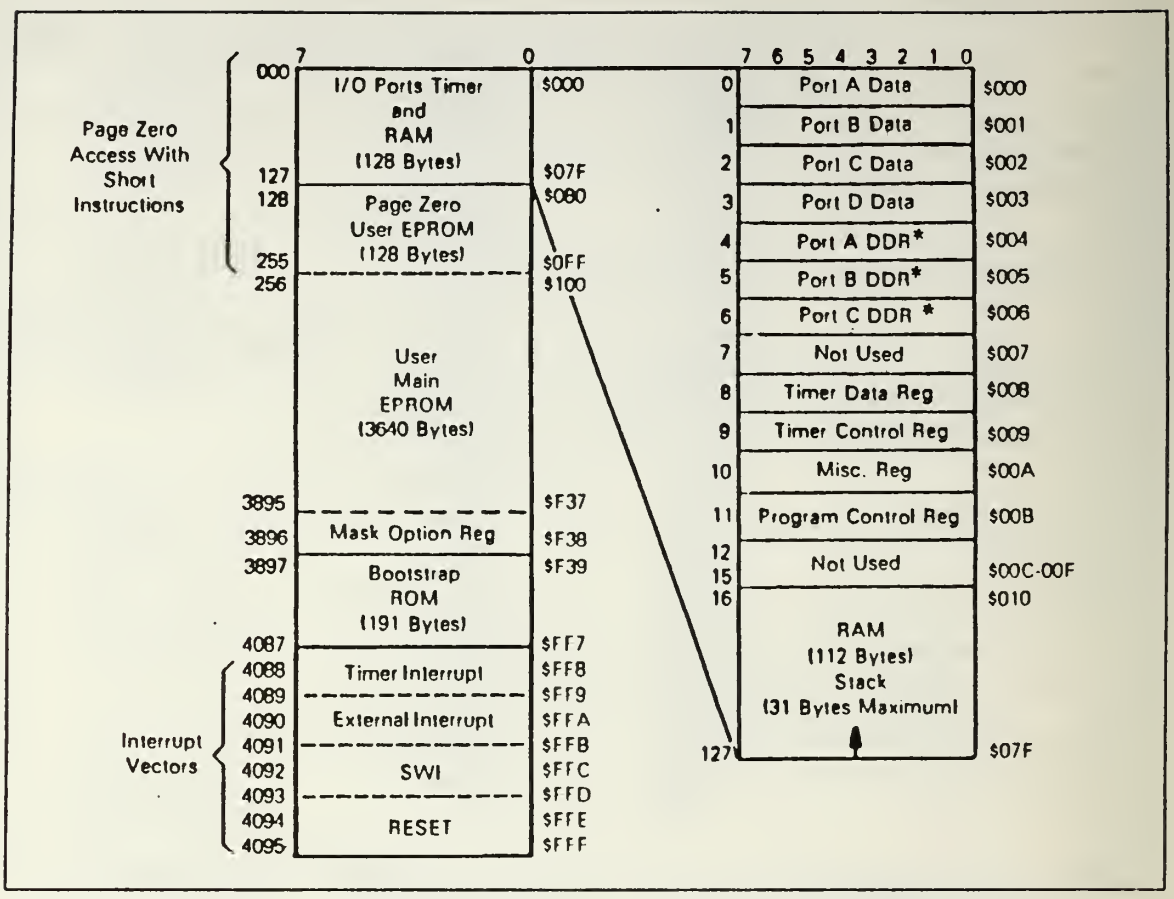


Figure 19. MC68705U3 Memory Configuration: From Ref. 10: p. 5.

Timer Interrupt Mask Bit (TIM) of the TCR is set. A brief description of each of the timer registers and their configuration follows.

(1) Timer Data Register (TDR). The TDR is the eight-bit counter which sets the TIR bit of the TCR when it decrements to zero.

(2) Timer Control Register. The contents of the TCR determine the general operation of the timer.

- Bit 7, Timer Interrupt Request (TIR), signals a TDR underflow when it is set and will cause a timer interrupt request if the TIM bit of the TCR is clear. The TIR is cleared by the MPU reset or by program control.
- Bit 6, Timer Interrupt Mask (TIM), inhibits a timer interrupt request when it is set. It is set by external reset or program control to inhibit the Blinking Mode, and is cleared by software when the Blinking Mode is requested by the operator.
- Bit 5, External or Internal Clock Select (TIN), is used to select the timer clock source. Since the internal clock is used in this application, the TIN bits of both

Table 3. MPU CONNECTIONS

Pin	Name	Description
1	V_{SS}	Ground
2	$\overline{\text{RESET}}$	When $\overline{\text{RESET}}$ is pulled low program execution halts, all variables are reinitialized and the Pan display is set to zero. SW1(P) controls the $\overline{\text{RESET}}$ line on the Pan MPU.
3	$\overline{\text{INT}}$	Allows asynchronous interruption of the processor. When $\overline{\text{INT}}$ is pulled low by the Count Edge Detector the MPU executes the "Count Routine".
4	V_{CC}	+5 V dc power connection.
5	EXTAL	External clock input. Connected to a 4.0 MHz external clock which provides the MPU system clock.
6	XTAL	Crystal clock input. Connected to ground since an external clock is used.
7	V_{PP}	Programming voltage pin. Connected to V_{CC} for normal operation.
8	Timer	External timer control input. Connected to V_{CC} since the internal timer is used.
	Port C	General Purpose I/O lines.
9	PC0	The two least significant digits in the display are represented in binary coded decimal (BCD) by these eight lines.
10	PC1	
11	PC2	
12	PC3	
13	PC4	
14	PC5	
15	PC6	
16	PC7	
	Port D	General Purpose input lines.
17	PD7	PD7 is the Channel A input to the MPU.
18	PD6/$\overline{\text{INT2}}$	PD6 is used as a second interrupt line. When PD6 goes low the MPU changes display modes.
19	PD5	PD5 is the Channel B input into the MPU.
20	PD4	PD4 is the Function input into the MPU.
21	PD3	PD3 is the Set input into the MPU.
22	PD2	PD2-PD0 are not used and are tied to ground.
23	PD1	
24	PD0	

Table 4. MPU CONNECTIONS (CONT'D.)

Pin	Name	Description
	Port B	General Purpose I/O lines (LED compatible).
25	PB0	The most significant digit is represented in BCD by PB0-PB3 except on the Tilt MPU where these lines are connected to ground. PB4 determines which digits in the display are blanked. PB5 is not used. Connected to ground. PB6 determines the presence or absence of the display minus sign. PB7 determines the presence or absence of the display decimal point.
26	PB1	
27	PB2	
28	PB3	
29	PB4	
30	PB5	
31	PB6	
32	PB7	
	Port A	General Purpose I/O lines.
33	PA0	The third and fourth least significant digits are represented in BCD by these eight lines.
34	PA1	
35	PA2	
36	PA3	
37	PA4	
38	PA5	
39	PA6	
40	PA7	

MPU's are always cleared. For the same reason the Timer pins are connected to V_{CC} (see Table 3).

- Bit 4, External Enable (TEE), is not used by the measurement system. By keeping the TEE clear at all times, the 68705's internal timer is used exclusively.
- Bit 3, Prescaler Clear (PSC), is not used in this application; always cleared.
- Bits 2-0, Prescaler Select (PS2, PS1 and PS0), are always set during program execution. This causes the internal timer signal frequency to be divided by 128.

(3) Mask Option Register (MOR). Unlike the TDR and TCR the MOR is not software programmable; instead, it is implemented in EPROM.

- Bit 7, the Clock bit, is cleared to allow operation of the external 4.0 MHz clock.
- The Timer Option bit (TOPT), bit 6, is also cleared in this application. This permits the TCR to be software programmable.
- Bit 5 is cleared to permit the use of the internal clock with the timer.
- Bits 4 and 3 are not used.

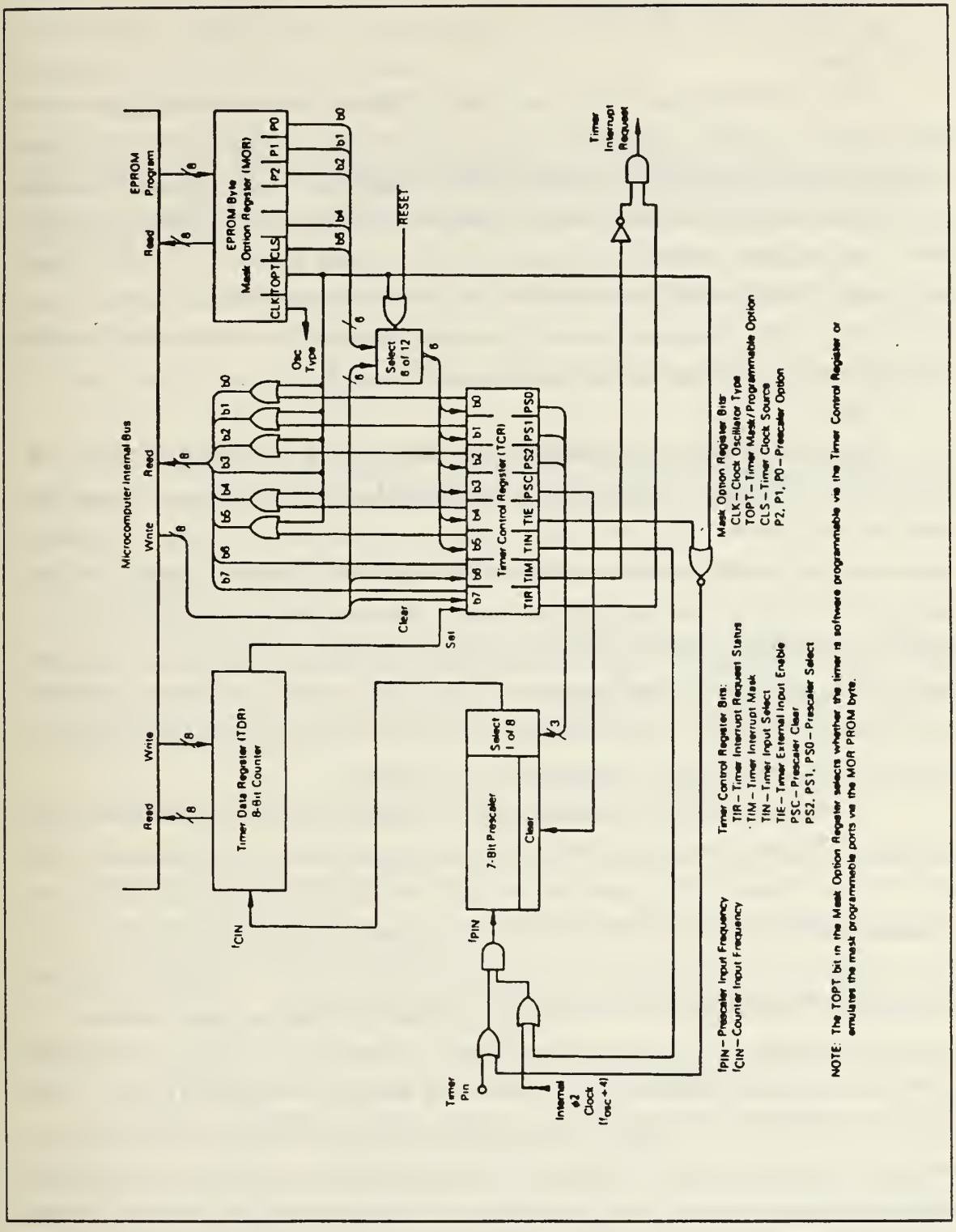


Figure 20. MC68705U3 Timer Functional Block Diagram.: From Ref. 10: p. 8.

- Bits 2-0 are all set and serve the same function as PS2, PS1 and PS0 bits of the TCR. [Ref. 10: pp. 6-8, 13-15]

3. RAM

The MC68705U3 has 112 bytes of RAM. The 112 bytes includes 31 bytes that can be used for the stack. Use of the stack is quite limited. During interrupts it is used to save the contents of the CPU registers and the program counter. During subroutine calls only the program counter is saved. The user's program has no other access to the stack. The programs written for each of the MPU's require less than 25% of the available RAM. The Pan MPU uses 27 of the 112 available bytes and the Tilt MPU uses only 22 bytes. The programs listed in Appendix D explain the function and give the location in memory for each of the variables. [Ref 10: p. 5]

4. ROM

The 3776 bytes of user EPROM in the MC68705U3 are divided into three separate blocks in the memory. Page Zero User EPROM is the ROM located between address S080 and S0FF. Because these addresses are only one byte long, instructions located in Page Zero ROM can be referenced with addressing modes not permitted with instructions located in other parts of the memory. Between address S100 and SF37 is the User Main EPROM. This portion of the memory in each MPU contains the vast majority of the signal conditioning programs. Located in another portion of the EPROM are the Interrupt Vectors. In each of these locations is the address of the first instruction the MPU is to execute when a particular interrupt occurs.

As with the RAM only a fraction of the available EPROM has been used in this application. The Pan MPU uses 899 bytes of the 3776 available and the Tilt MPU uses only 767 bytes. Since both programs are so small, one could reasonably ask why the two programs were not both put in one MPU. The primary problem with this idea is that each microprocessor can perform only one operation at a time. As indicated at the end of Chapter II, if the camera servo is rotating about its vertical axis at its maximum velocity of 1 rpm, the Pan signal conditioner must be capable of counting and displaying 51,200 counts per minute. Using a 4.0 MHz clock this allows the MPU 1172μs to count each pulse. Similarly the Tilt MPU has 1758μs to count each pulse when the camera is rotating at its maximum velocity about the horizontal axis. Assuming that the camera is rotating at its maximum velocity on both axes at the same time, and one MPU is being used to count the pulses from both encoders, the MPU needs to count 76,800 pulses per minute, which only allows 781.3 μs per pulse. The Pan MPU currently requires a max-

imum of 1032 instruction cycles or 1032μs to count a single pulse, and the maximum execution time for a single pulse on the Tilt axis is 825μs. Thus, a single 68705 lacks the computational speed required to ensure that no counts would be missed if it was used to process the data from both encoders.

5. Central Processing Unit (CPU)

> The CPU of the M6805 Family is implemented independently from the I/O or memory configuration. Consequently it can be treated as an independent central processor communicating with I/O and memory via internal address, data and control buses. [Ref 10: p. 6]

The CPU has five registers that are available for use by the operator. The function of each of these is described below.

- The Accumulator (A) is a general purpose data register used for arithmetic calculation and data manipulation.
- The Index Register (X) can be used as a second accumulator but is generally used for the indexed addressing mode. In the indexed addressing mode an effective address is created by adding the contents of X to a number provided by the instruction.
- The Program Counter (PC) contains the memory address of the next instruction to be executed by the MPU.
- The five bits of the Condition Code Register (CCR) keep information concerning the results of the last instruction executed by the MPU. Reference 14 gives a detailed description of each of the instructions in the M6805 Family Instruction Set and explains the effect of each instruction on the CCR. A brief description of each bit in the CCR follows.
  - The Carry (C) bit is set if a carry or a borrow was generated by the last arithmetic instruction. The state of the C bit can be software controlled.
  - The Zero (Z) bit is set if the result of the last arithmetic, logic or data manipulation instruction was zero.
  - The Negative (N) bit is set if bit seven of the result of the last arithmetic, logic, or data manipulation instruction is set.
  - The Half Carry (H) bit is set if an ADD or an ADC instruction causes a carry to occur between bits 3 and 4 of the result.
  - The Interrupt Mask (I) bit is set when an external interrupt ($\overline{INT}$) occurs. If another interrupt occurs (e.g. Timer Interrupt or $\overline{INT2}$) when the I bit is set, the second interrupt is latched so that it can be processed as soon as the I bit is cleared. The I bit can be set or cleared by software.
- The contents of the Stack Pointer (SP) are the address of the next available location on the stack. As previously discussed, the stack is only used to keep track of the PC during subroutine branches, and all of the CPU registers during an interrupt. [Refs. 10: p. 6, 14 : pp. 14-15]

6. Input

Each MPU uses six input lines. Two of these lines, $\overline{INT}$ and $\overline{INT2}$, are interrupt lines that detect a negative-going edge on their respective lines. The other four lines are general purpose input lines on Port D. All of the pins on Port D are TTL compatible which made the hardware design relatively straightforward. The electrical characteristics for the input pins are listed on p. 2 of Ref. 10.

The general operation of the two interrupt lines is described in Table 3 on page 39. Once they are understood, interrupts are a simple yet powerful tool. Only three of the four interrupts available on the MC68705U3 are used by the Pan and Tilt programs. The software interrupt is not used. When the MPU is interrupted, current program execution is halted, the contents of the CPU registers are placed on the stack, and the MPU fetches the contents of the appropriate interrupt vector from memory. After the interrupt vector has been fetched, the PC is moved to that address and execution of the interrupt routine begins. There is no ambiguity when an external interrupt occurs since there is a dedicated interrupt vector in memory. The timer interrupt and $\overline{INT}$ however share the Timer Interrupt Vector. When one of these interrupts occurs, the interrupt routine must determine the source of the interrupt by checking the TIR bit of the TCR and bit 7 of the MR to determine the source of the interrupt [Ref. 10: p. 11]. Normal program execution resumes at the point at which the interrupt occurred when the interrupt routine executes a return from interrupt (RTI) instruction.

The Function and Set lines on pins 20 and 21 are connected to the Function and Set switches. The operation of these switches is described in Table 2 on page 36. The remaining two input lines to each MPU are Channels A and B from the respective shaft encoders. The MPU programs use the information from these two inputs to determine the direction of rotation and to identify repeated oscillations about a single transition.

7. Output

Each MPU is designed to provide position information at its output in two basic forms. On the Pan axis, in the Count Mode a number between -51,200 and +51,200 constitutes the output while in the Position Mode the output is an angle between 0° and 360°. A five digit display with a minus sign is sufficient for the count display. Using a five digit display with a decimal point in the Position Mode permits the angle to be displayed to the nearest hundredth of a degree. This resolution is not quite as good as the resolution of the shaft encoders ($\pm 0.007°$); however, final testing of the measurement system revealed that resolution is actually limited to about $\pm$ 0.02° on the Pan axis and

about $\pm 0.14°$ on the Tilt axis. The five digit display is therefore completely adequate for this system.

The Pan MPU uses 23 of its 24 output pins to represent the five digits, a minus sign and a decimal point. Each of the five digits is available in BCD form on four output pins of the MPU. The five digits are referred to as Digit 1, Digit 2, etc., with Digit 1 being the least significant digit and Digit 5 being the most significant digit. Port A has as its output the BCD representation of Digit 3 and Digit 4. Digit 1 and Digit 2 are represented by the output of Port C. The low four bits of Port B contain the BCD representation of Digit 5. These 20 output lines are the input to five 74LS47, BCD/7-Segment Decoder/Drivers, which decode the BCD signals and drive the common anode LED indicators. The output from Pin 29, PB4, is one input to a 74LS32 OR gate, the output of which is used to blank leading zeros out of the display. Pin 30 is not used and is tied to ground. The remaining two output pins drive two LED segments in the display. The signal on pin 31 turns the minus sign off and on, and the signal on pin 32 determines whether the decimal point is displayed.

The electrical characteristics of the I/O Ports are given on p. 4 of Ref. 10. The output characteristics of Ports A, B and C are compatible with the input characteristics of the 74LS47 and the 74LS32 given on pp. 4-59 and 4-48 of Ref. 11. The pins on Port B are capable of sinking 10 mA when Port B is configured as an output port. A 220 Ω resistor placed in series with each of the display segments limits the current to approximately 9 mA and permits the MPU to drive the decimal point and minus sign directly.

One consideration in the design of this system was to provide a system capable of being readily expanded to meet changing needs. To this end, in addition to being connected to the LED display devices via the 74LS47's, the BCD data lines are also connected to a header on each of the MPU circuit boards. If, at a later date, the position information needs to be used in another system, a jumper connected to each of the headers could provide the information with little or no modification.

The Pan and Tilt signal processing subsystems are virtually identical in the hardware used to implement them. The only difference is that the Pan system has a five digit display, and the Tilt system needs only four digits to display its position information. Consequently, the Tilt system does not use Digit 5, and pins 25-29 are tied to ground.

F. DISPLAY

Each digit represented in BCD at the output of the MPU is decoded by a 74LS47 BCD/7-Segment Decoder/Driver. The decoding devices each convert a four bit BCD representation of a number into seven signals that each drive a separate segment of a common anode, seven segment, LED display. The 74LS47 is capable of sinking 24 mA from each of the LED segments. Without a current limiting resistor between each of the output pins on the 7447 and the corresponding pin on the display element however, this maximum current is exceeded. When this happens the LED's have a very short life, the 7447 overheats and the system fails to function properly. The addition of a 220 Ω resistor in each branch limits the current to about 9 mA per segment, and permits trouble-free operation.

Three of the output pins on each MPU are not used as inputs to the 7447's. As discussed in the previous section, the Decimal and Minus lines each drive individual LED segments directly. The third line, also mentioned briefly in the preceding section, is used with the Blanking In/Ribbon Blanking Out (BI/RBO) signal from Digit 4's 7447 to determine the Ribbon Blanking In (RBI) signal into the 7447 which drives the display for Digit 3.

The term "blanking" simply means removing the leading zeros from the display. The two display modes available from the MPU's have different blanking requirements. In the Position Mode the three least significant digits are not blanked, while in the Count Mode, all but the least significant digit are blanked. The RBI and BI/RBO pins on the 7447's, the Blank line out of each MPU and the OR gates, connected as shown in the schematics in Appendix A, provide this capability.

The Light Test (LT) pin on each 7447 is connected to SW5. When the switch is closed, the Light Test line goes low and each of the output lines on each of the 7447's also goes low, thus sinking current from all of the LED segments simultaneously. This feature allows the operator to check for inoperable display segments.

G. POWER SUPPLIES

The two power supplies shown in Figure 2 on page 6 are each +5.0 Vdc supplies. The power supply which provides power to the shaft encoders and the line drivers is physically mounted in the camera housing. It was built by modifying the +12 Vdc auto iris power supply. This was accomplished using an LM7805 Voltage Regulator in the manner shown in Figure 8 of Appendix A. The auto iris requires only 100 mA at +12 Vdc for correct operation, and the LM7812 Voltage Regulator has an available

output current of 1.0 A [Refs. 15, 16]. The remaining 900 mA is available to the LM7805 to power the encoders and the line drivers. Reference 9 lists the maximum power requirement for the HEDS-600 as 40 mA at +5 Vdc, and Ref. 11 specifies the maximum power requirement for a 74S140 is 1 mA at +5 Vdc. Thus, the 84 mA requirement for the two encoders and four line drivers is well within the capabilities of the modified power supply.

The second power supply is capable of providing 6.0 A at +5 Vdc which is more than adequate to provide the 1.4 A needed by the signal processors and the display devices. The power supply also has 12 Vdc and -5 Vdc ports. To preclude the potentially disastrous results which might occur if the power supply were incorrectly connected to the signal processor/display devices, the circuitry shown in Figure 21 was included on each MPU and display printed circuit board.

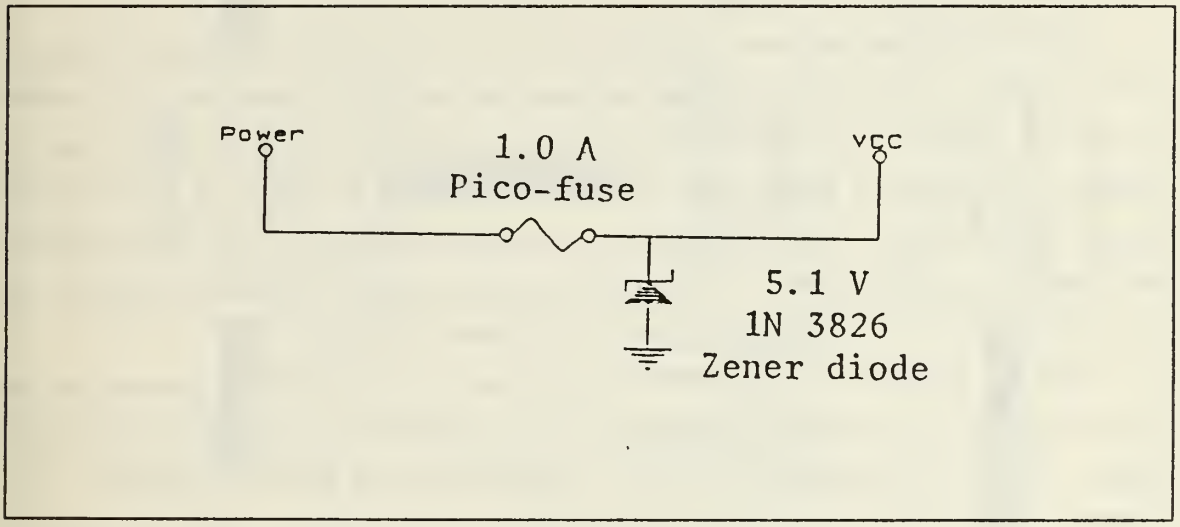


Figure 21. Reverse/Over-voltage Protection Circuit

IV. CALIBRATION , TESTING AND IMPLEMENTATION

A. GENERAL

Once the basic system design had been completed, and the MPU programs had been written, a prototype system was constructed. The prototype system might also be called the development model, since it was not only used to test the design , but was also used to calibrate the MPU programs. A block diagram of the prototype system is shown in Figure 22. The M68705EVM Evaluation Module (subsequently referred to as the EVM) provided the capability to debug and evaluate the MC68705U3-based signal processing subsystem. Operation of the signal processing MPU was performed by an MC68705U3 resident on the EVM.

The prototype system provided considerable flexibility in the testing and calibration of the system. The assembly language programs for the MPU's were written and edited on the PC. They were then assembled and linked using the 2500 A.D. 6805 Cross Assembler and 2500 A.D. Linker [Ref. 17: pp. (1-1)-(2-38)]. The result, a Motorola S19 output file (see [Ref. 17: pp. (A-1)-(A-4)]), was then down-loaded to the EVM using the file transfer program, Kermit. Downloading procedures are detailed in [Ref. 18: pp. (3-10)-(3-25),(3-37)]. The PC-EVM interface is shown in Figure 23.

After the program had been down-loaded into the MC68705U3 resident on the EVM, data entry and program debugging were controlled via the CRT monitor keyboard. The CRT-EVM interconnection is shown in Figure 24 and the monitor commands are described in [Ref. 18: pp. (3-8)-(3-25)].

The remainder of the signal processing functions were realized using hardware external to the EVM. These functions included edge detection of the output signals from the shaft encoders, decoding the output of the MPU, and generating the signals to drive the display devices. This portion of the prototype, referred to by [Ref. 18] as the "target system", was built on breadboards and is represented by the block in the center of Figure 22. The target system was connected to the MCU via a 40-pin jumper header, J1, on the EVM. The pinout for J1 is shown in Figure 25. The labels in Figure 25 refer to the labels used in the schematic diagrams which are shown in Appendix A.

B. CALIBRATION

Once the MPU programs were capable of counting the pulses generated by the shaft encoders, the programs needed to be "calibrated". This calibration procedure required

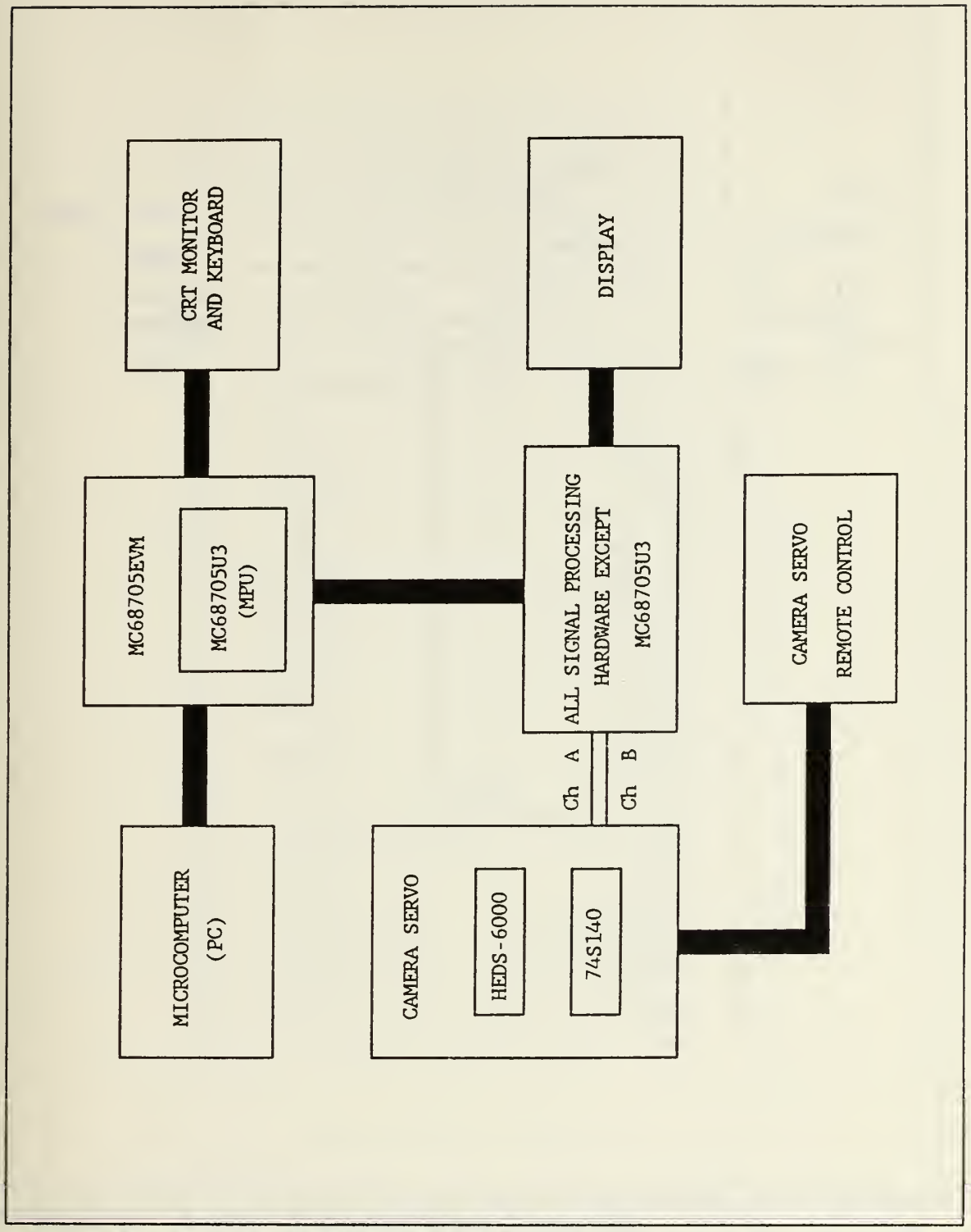


Figure 22. Prototype/Development Model

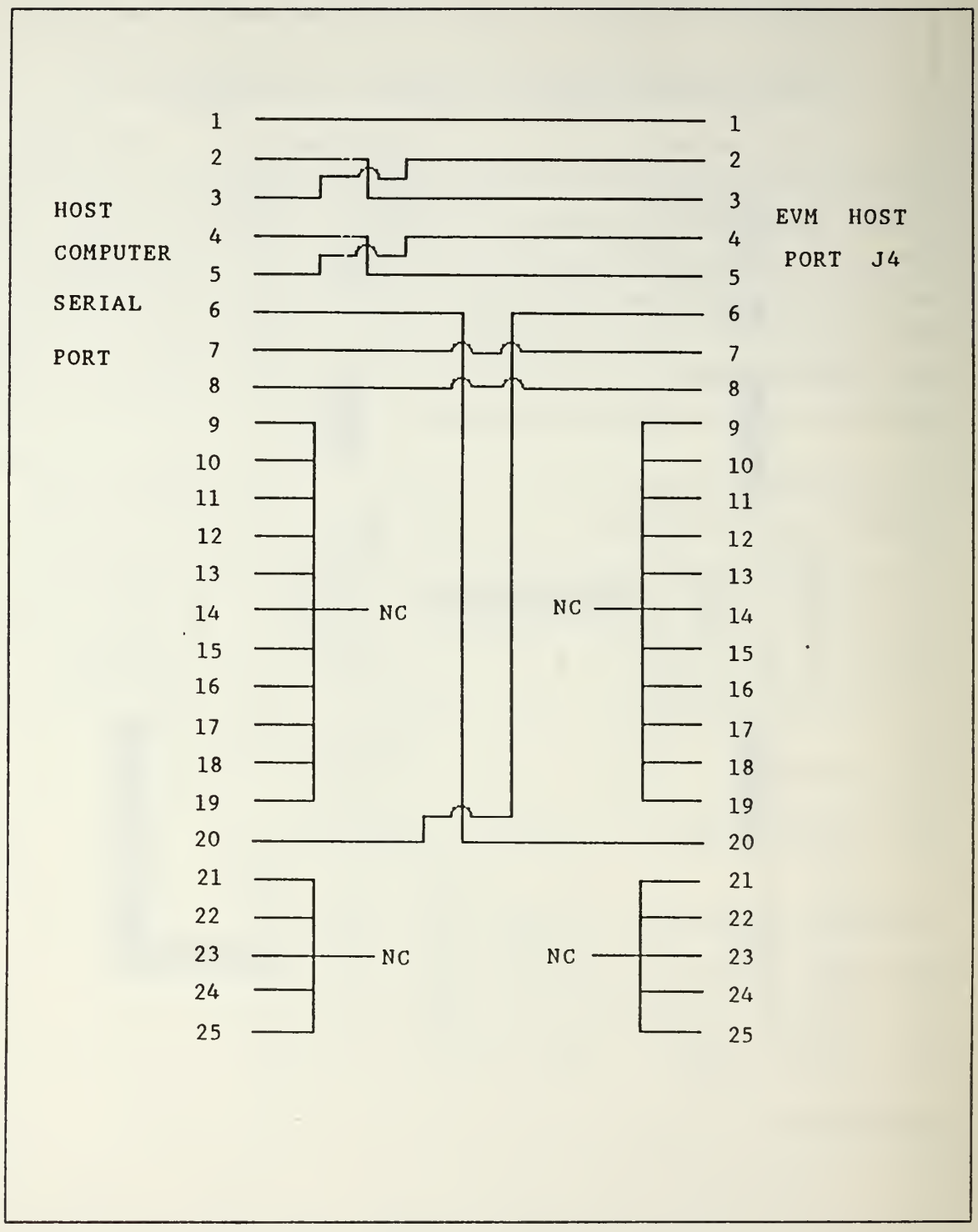


Figure 23. Host Computer - Evaluation Module Connections

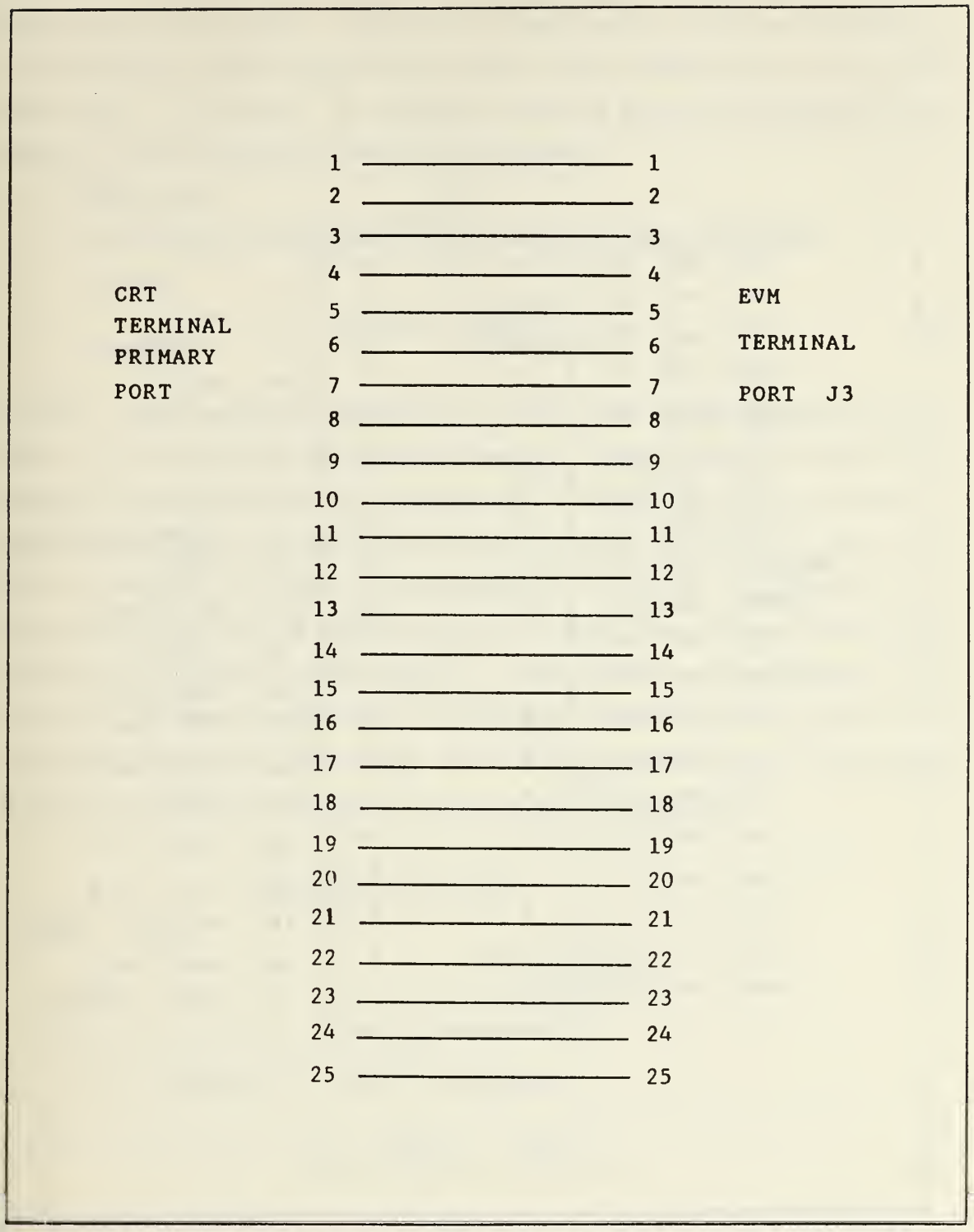


Figure 24. Monitor - Evaluation Module Connections

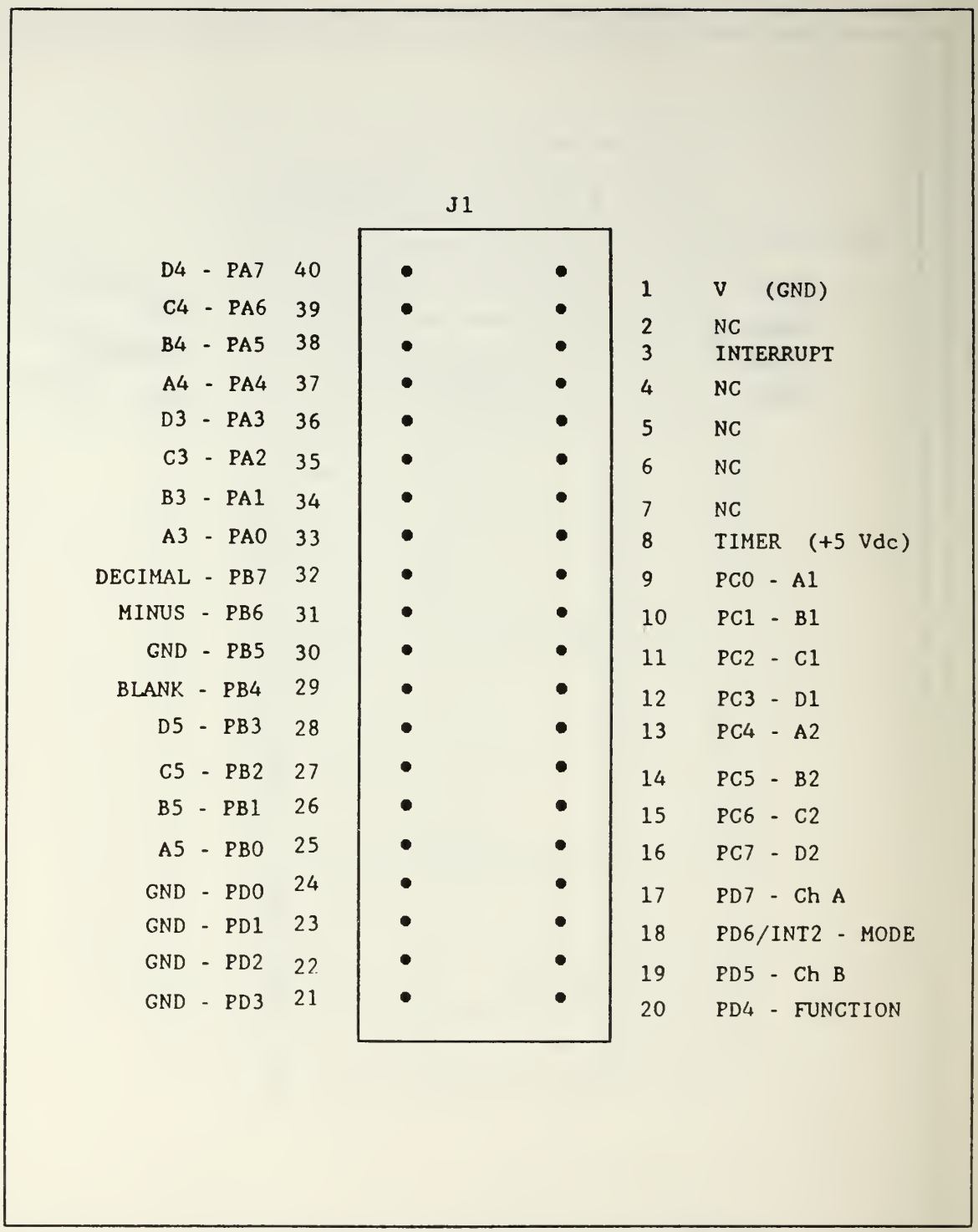


Figure 25. Evaluation Module - Signal Processor Connections

determining the angular distance through which the camera rotated between successive pulses from the shaft encoder. This number is a scale factor, which, when multiplied by the total number of pulses from the shaft encoder, yields a number equal to the angular displacement of the camera. The calibration procedure also involved determining the amount of hysteresis present in each of the gear trains.

1. Scale Factor

To determine the scale factor (SF) the simple geometric relationship

$$\theta = \tan^{-1}\left(\frac{\text{opposite}}{\text{adjacent}}\right) \tag{12}$$

was used. Using a small laser attached to the camera servo, and the geometry shown in Figure 26, the SF could be experimentally determined. As the camera servo was rotated through an angle, θ, the MPU was used to count the output pulses from the shaft encoder. The laser beam was projected on a vertical surface at a distance, a, away from the axis of rotation. The beam of the laser spread to a diameter of approximately 0.4 in. over a distance of 30 ft. A template with a 0.4 in. diameter aperture was used to mark the location of the "spots" on the distant wall. The distance between the spots, l, was measured by selecting one edge of one of the marks and measuring the distance to the corresponding edge of the distant mark. Then, having determined l and a and reading the count, C, from the display, the SF could then be determined from

$$\begin{aligned} \text{SF(degrees/Pulse)} &= \frac{\theta}{\text{C}} \\ &= \frac{\tan^{-1}\left(\frac{l(\text{in})}{a(\text{in})}\right)}{\text{C}} \end{aligned} \tag{13}$$

Using Equation (13) to simplify the expression,

$$\text{d(SF)} = \frac{\delta(\text{SF})}{\delta l}\,\text{d}l + \frac{\delta(\text{SF})}{\delta a}\,\text{d}a \tag{14}$$

yields

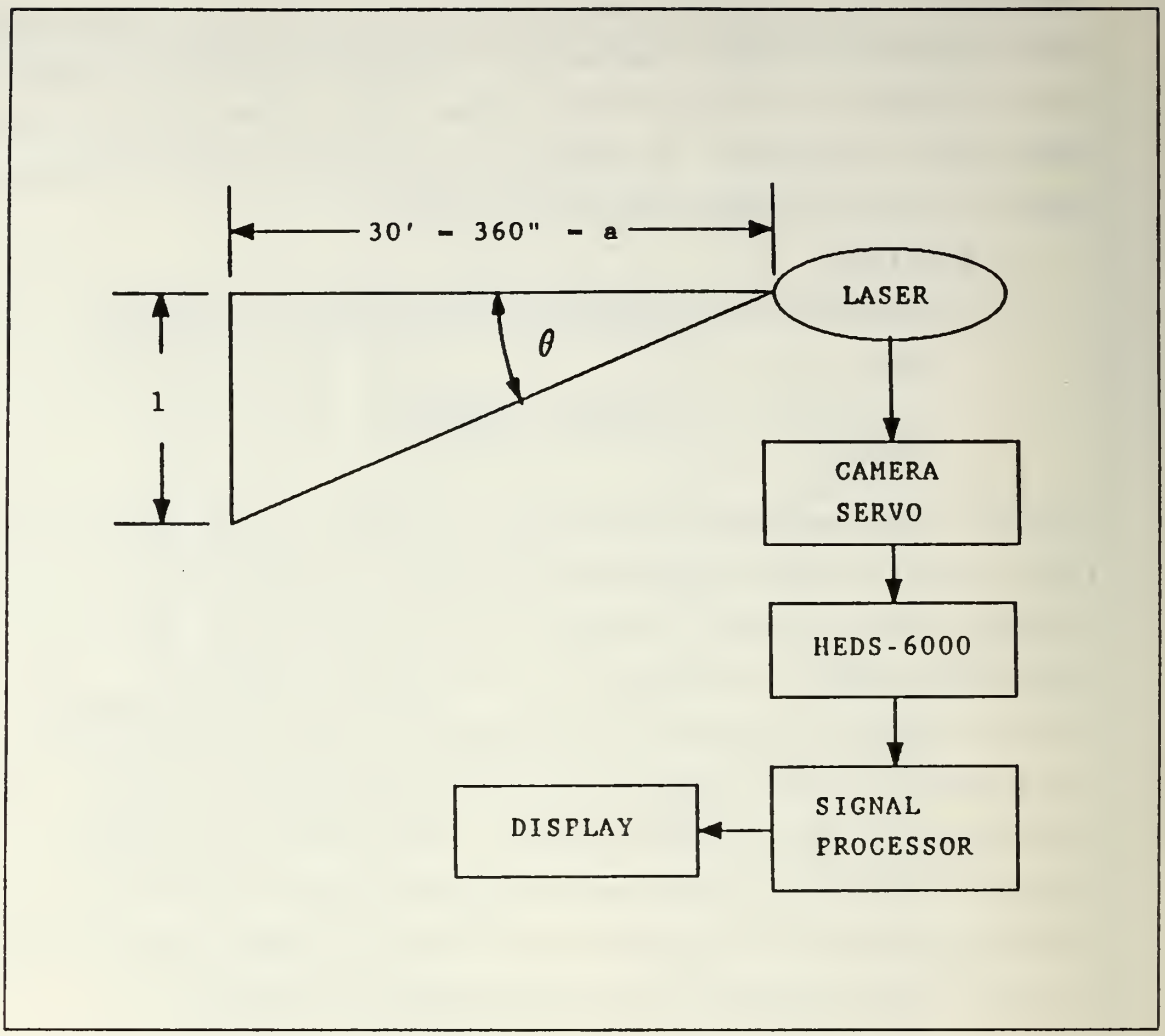


Figure 26. Geometry Used to Determine the Scale Factor

$$
\begin{aligned}
d(SF) &= \frac{1}{C}\frac{\delta\theta}{\delta l} + \frac{1}{C}\frac{\delta\theta}{\delta a}\,da \\
&= \frac{1}{C}\left(\frac{a}{a^2+l^2}\right)dl + \frac{1}{C}\left(-\frac{l}{a^2+l^2}\right)da \qquad (15) \\
d(SF) &= \frac{(a\,dl - l\,da)}{C(a^2+l^2)} \quad ,
\end{aligned}
$$

which indicates that C, a and l should all be as large as possible to minimize the error in SF due to a measurement error in a or l. The physical size of the laboratory limited the distance, a , to 30 ft. When $a = 30$ ft, l was limited to about 3.5 ft in the horizontal

plane and about 4.0 ft in the vertical plane. By modifying the geometry as shown in Figure 27, the count, which from Equation (13) is directly proportional to θ, could also be maximized. The configuration shown in Figure 27 was used to obtain the scale factor calibration data for the Pan axis. However, since the servo is incapable of rotating 360° about the Tilt axis, the test configuration shown in Figure 26 had to be used the collect the data for that axis.

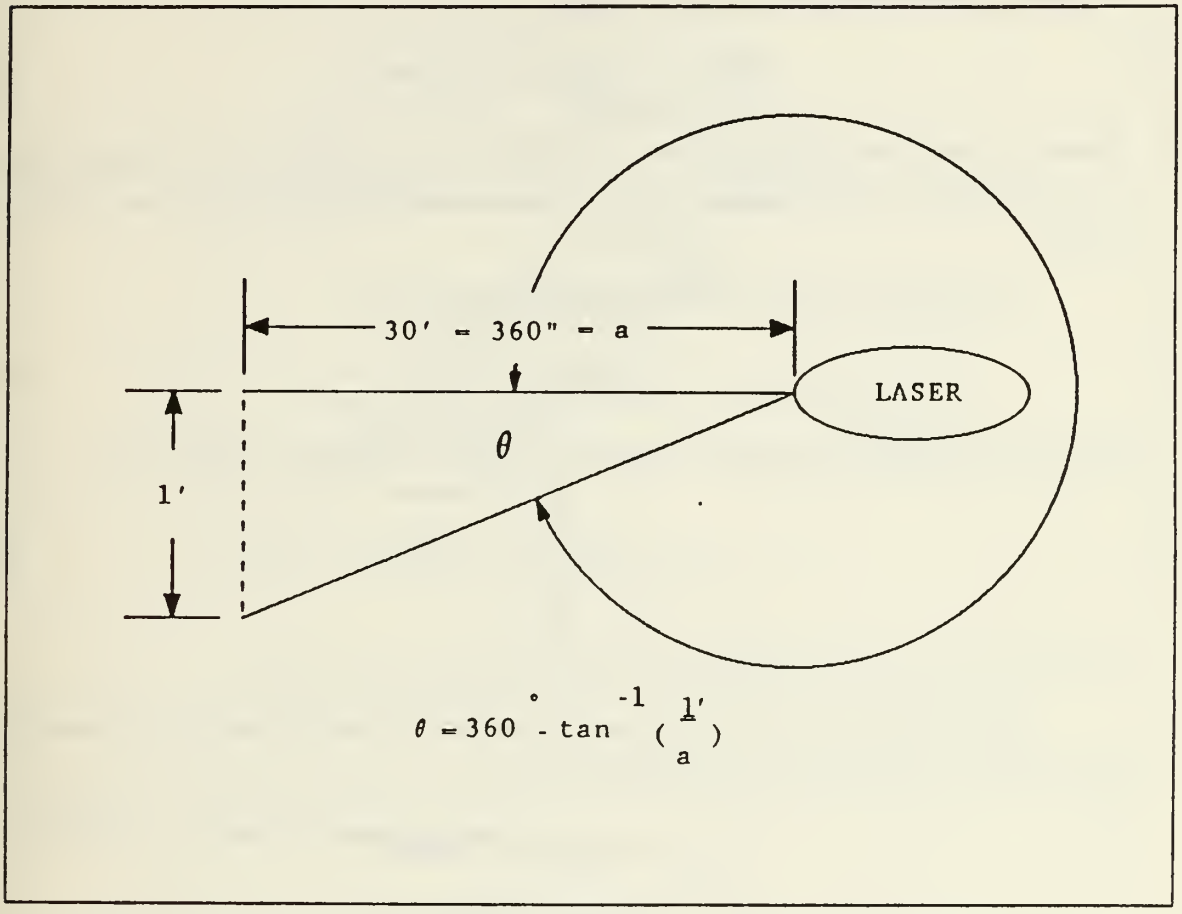


Figure 27. Alternate Geometry Used to Determine the Scale Factor

Adopting the notation, $\overline{X}$, to represent the mean value of a random variable, X; if X is discrete with N measured values,

$$\overline{X} \simeq \frac{1}{N} \sum_{i=1}^{N} X_i \qquad (16)$$

where X_i is the ith measured value of X, and the approximation becomes better as N approaches infinity.

Using the expression in Equation (16) and the measured data for the scale factors, from 31 measurements on the Pan axis,

$$\overline{SF}_{Pan} = (7.0312 \times 10^{-3})^{\circ}\text{Pulse}^{-1} \quad , \tag{17}$$

and after 32 measurements on the Tilt axis,

$$\overline{SF}_{Tilt} = (7.0452 \times 10^{-3})^{\circ}\text{Pulse}^{-1} \quad , \tag{18}$$

where the subscripts indicate the axis. The actual implementation of these scale factors is described later in this chapter and in the documentation for each of the MPU programs.

If the error in the ith measurement is described by

$$e_i = X_i - \overline{X} \quad , \tag{19}$$

then the root mean square (RMS) error in N measurements of X is given by;

$$\sigma_x = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - \overline{X})^2} \quad . \tag{20}$$

Note that this is also the definition of the standard deviation of X.

The RMS errors in the Pan and Tilt scale factor measurements were determined from Equation (20) and the measured data to be;

$$\sigma_{SF_{Pan}} = (4.62 \times 10^{-6})^{\circ}\text{Pulse}^{-1} \tag{21}$$

$$\sigma_{SF_{Tilt}} = (6.89 \times 10^{-6})^{\circ}\text{Pulse}^{-1} \quad . \tag{22}$$

As before, the subscripts are used to identify the axis and the source of the error. The fact that the errors are small compared to the mean values suggests that the means should closely approximate the actual values for the scale factors.

2. Hysteresis

Houghton defines backlash in wormgearing as "...the total play between the surfaces of the worm and worm wheel teeth measured normal to the faces." [Ref. 19: pp. 1.4, 1.5] Backlash only poses a problem in the measurement system when the servo's

direction of rotation changes. Figure 28 is a typical hysteresis curve. As long as the direction of rotation of the worm is increasing the $\theta_{WORM}/\theta_{WORMGEAR}$ relationship is linear. However, when the direction of rotation reverses there is a region, depicted by the left pointing arrows, where the position of the worm changes without a corresponding change in the position of the wormgear. Note that once all of the backlash has been taken up the $\theta_{WORM}/\theta_{WORMGEAR}$ relationship is again linear until the direction of rotation changes.

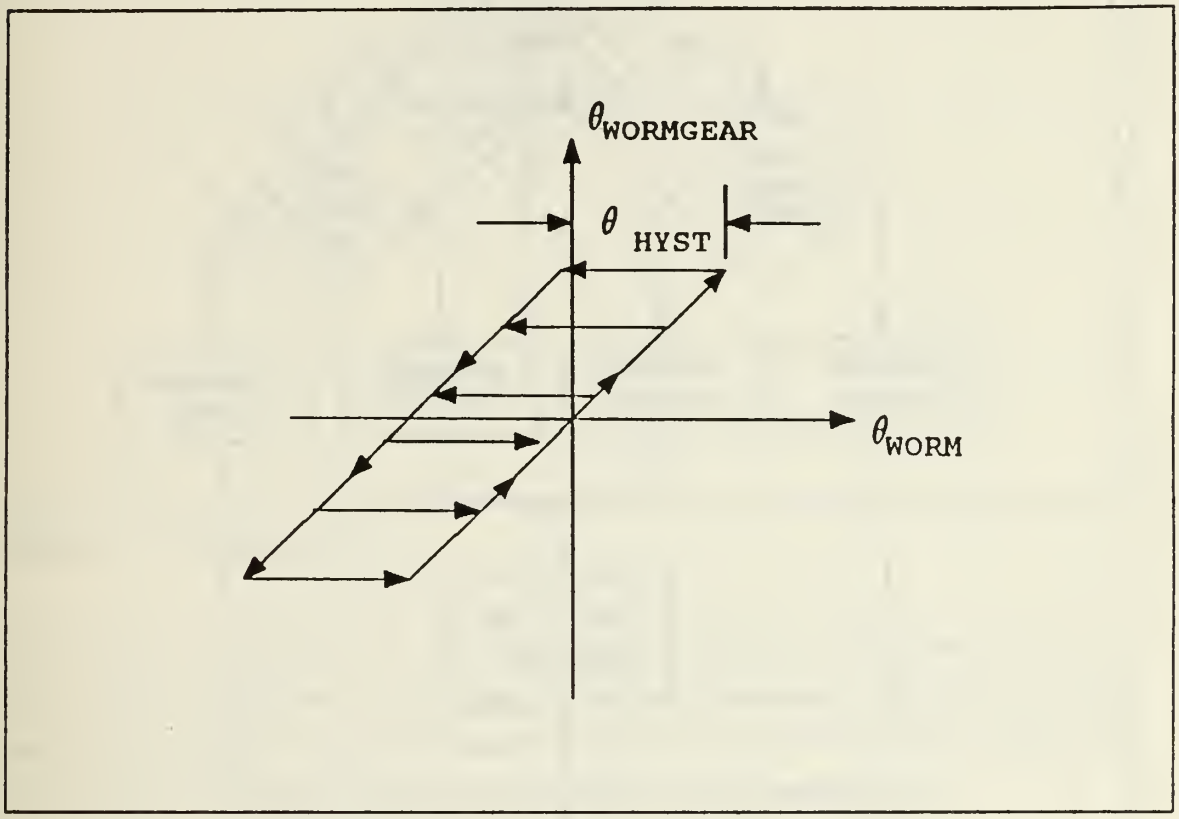


Figure 28. Typical Hysteresis Curve

The purpose of the hysteresis buffer in the MPU is to permit the signal processor to account for the backlash error introduced into the measurement by the worm-wormgear connection. The theory of operation for the buffer is relatively straight forward and is best described by the flow diagram in Figure 29. The buffer is a data byte in the MPU RAM. As long as the buffer is full, i.e., the contents are equal to the predetermined buffer length, a clockwise (CW) signal from the shaft encoder (increasing elevation and increasing azimuth are defined as CW rotation for the purposes of this system) causes the position counter to be incremented. Similarly, counter-clockwise

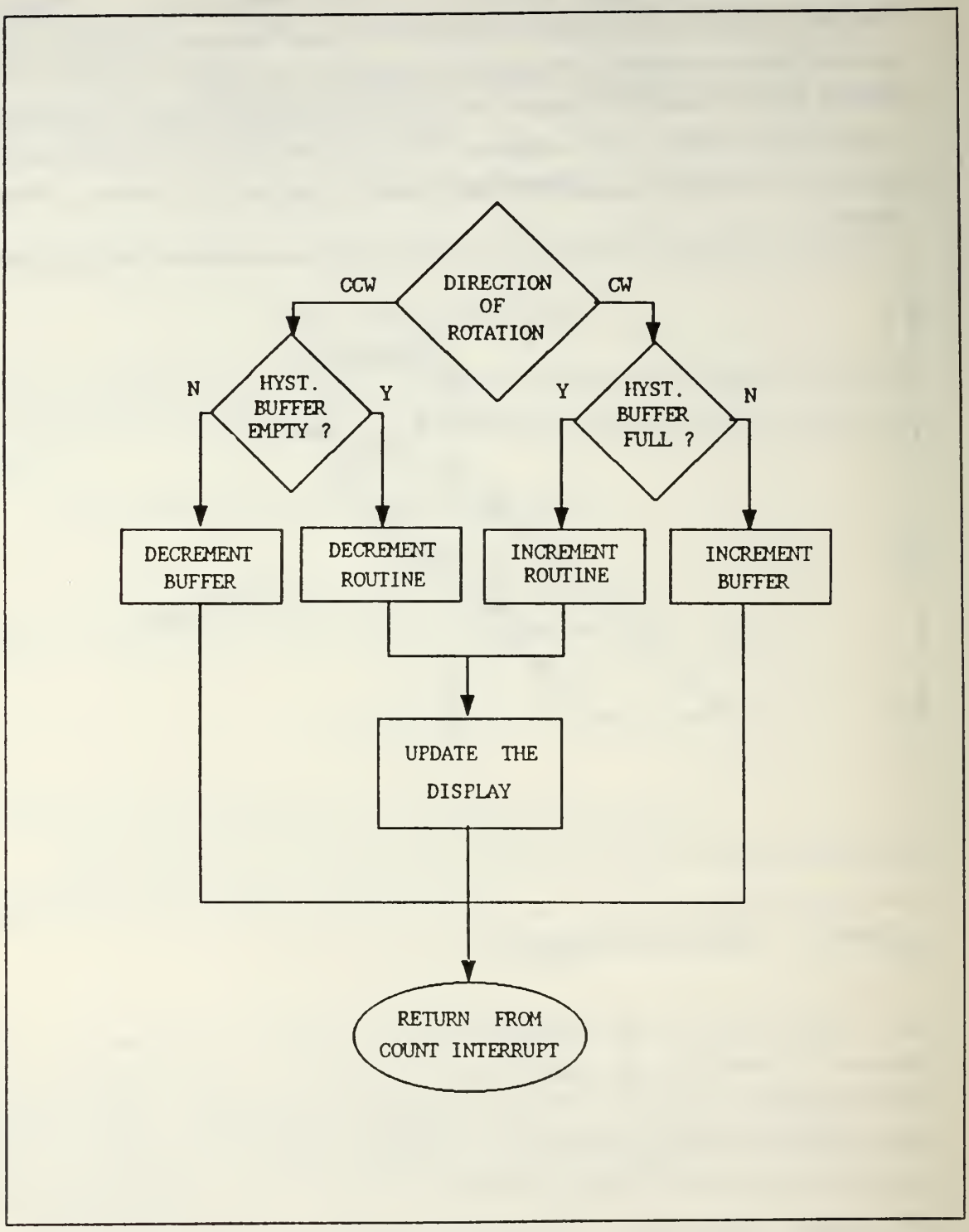


Figure 29. Operation of the Hysteresis Buffer

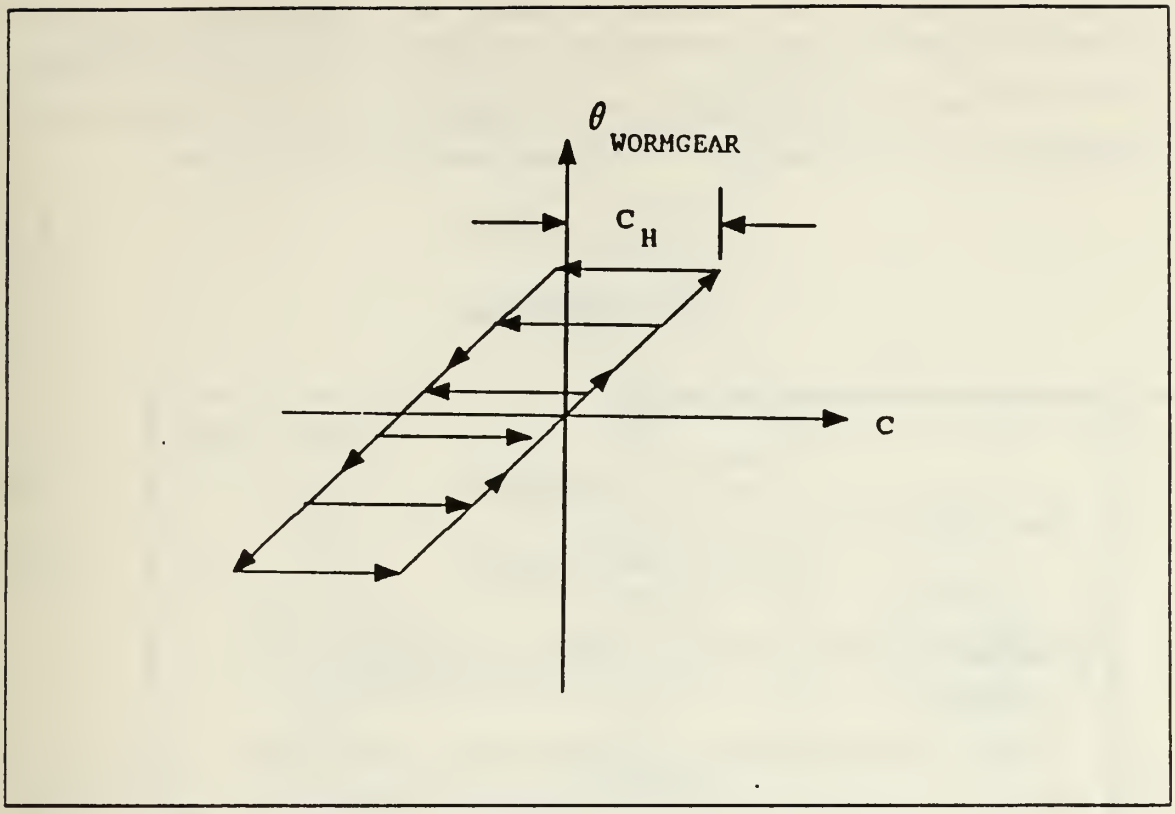


Figure 30. Hysteresis Curve

(CCW) signals cause the position counter to be decremented if the hysteresis buffer is empty, i.e., the contents are equal to zero. These two situations correspond to the two linear sections in Figure 28. From Equation (13), the horizontal separation of these two lines is related to the length of the hysteresis buffer, C_H by the expression

$$C_H = \frac{\Delta\theta_H}{SF} \quad . \tag{23}$$

Similarly, using the $\overline{SF}$ to map θ_{WORM} into C, and the fact that the displacement of the wormgear equals the displacement of the axis of interest, the curve shown in Figure 30 can be obtained from Figure 28. From Figure 30 it is apparent that two different pulse counts can be obtained for any given position, θ, depending on whether that position is approached from a CW or a CCW direction. The difference in the two counts is a measure of the hysteresis present in the gear train and is also the required length for the hysteresis buffer. By using this difference as the length of the hysteresis buffer, counts received by the MPU which occur while the gears are operating on one of the horizontal

sections of the curve in Figure 30 are not considered "valid" and therefore do not cause the MPU to modify the position. Using Equation (23) and data collected in the laboratory the average hysteresis present in each of the gear trains was determined (from 45 measurements on the Pan axis and 30 measurements on the Tilt axis) to be

$$\overline{C}_{H(Pan)} = 7.39 \text{ Pulses} \tag{24}$$

$$\overline{C}_{H(Tilt)} = 6.06 \text{ Pulses} \tag{25}$$

and the RMS errors were calculated to be,

$$\sigma_{C_{H(Pan)}} = 1.0 \text{ Pulses} \tag{26}$$

$$\sigma_{C_{H(Tilt)}} = 0.91 \text{ Pulses} . \tag{27}$$

C. IMPLEMENTATION OF THE CALIBRATION DATA

1. Background

Figure 31 outlines the basic operation of each of the MPU's. Although each of the routines is described in detail by the comments included in the programs, the operation of the Count Routine is the heart of the program and should be explained prior to discussing the actual implementation of the experimental results.

When the system operator causes the camera servo to rotate, each optical shaft encoder translates the displacement of one of the axes into two series of digital pulses. The two pulse trains, referred to as Channels A and B, are TTL logic level signals. When the logic level of Channel A transitions from low to high (rising edge transition) or from high to low (falling edge transition), the edge detector (See Figure 15 on page 33) pulls pin 3 of the associated MPU low for approximately 2 μsec. When this occurs an external interrupt (EXT INT or $\overline{\text{INT}}$) request is generated and the MPU begins execution of the Count Routine.

As mentioned in Chapter III, since both rising and falling edge transitions are detected by the edge detector, the signal processor must be capable of detecting multiple oscillations of the shaft about a single logic level transition point. Accordingly, the first tasks performed by the Count Routine are to determine the direction of rotation and to simultaneously determine whether the interrupt is the result of a stationary shaft oscillation. To do this the Count Routine checks the state of pin 17 (Channel A) and pin 19 (Channel B). Operation of this portion of the routine is summarized in Table 5.

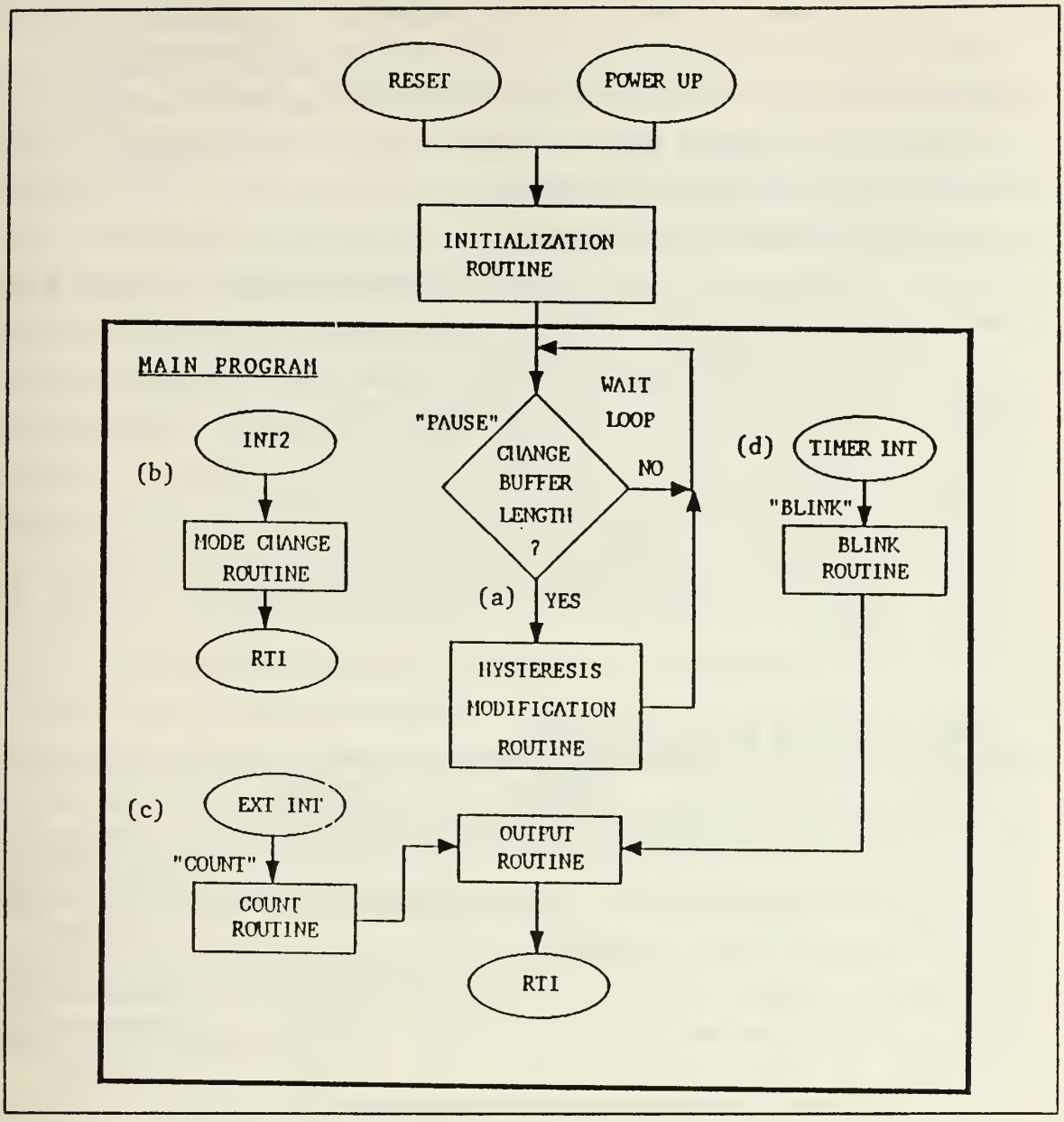


Figure 31. Program Flow Diagram: Program executes in the Wait Loop until; (a) the operator requests to modify the hysteresis buffer, (b) the operator requests to change the display mode, (c) an external interrupt is generated by the Channel A edge detector or, (d) a timer interrupt causes the display mode to "blink". All interrupt routines are terminated with a return from interrupt (RTI) command.

Note that CW rotation is indicated when Channel B leads Channel A in phase and CCW rotation is indicated if Channel A is leading Channel B. The possibility of erroneously counting multiple oscillations about a single point is eliminated by "counting" only the leading edge transitions when the shaft is rotating CW and only the trailing edge transitions when the rotation is CCW. All other transitions cause the program to execute a "return from interrupt" (RTI) instruction.

2. Implementing the Hysteresis Buffer

The transitions that are to be counted cause the program to compare the contents of the hysteresis buffer, HYSTCT, and the direction of rotation to the experimentally determined buffer length, HYST$\simeq\overline{C}_H$. If the rotation is CW and the buffer is full (i.e., HYSTCT = HYST), or if the rotation is CCW and the buffer is empty (i.e., HYSTCT = 0), then the "slack" due to the gear backlash should have been taken up , the transitions are considered "valid" and the MPU modifies the position appropriately. "Invalid" counts cause the contents of the hysteresis buffer to be incremented or decremented depending on whether the present direction of rotation is CW or CCW (Figure 29 refers).

Table 5. COUNT ROUTINE LOGIC

Channel A	Channel B	Direction of Rotation	Count the Pulse?	Action
Low	Low	CW	No	Increment the hysteresis buffer.
Low	High	CCW	Yes	Decrement the position.
High	Low	CCW	No	Decrement the hysteresis buffer.
High	High	CW	Yes	Increment the position.

From the calibration data for the Pan axis, $\overline{C}_{H(Pan)}\simeq 7.4$ and $\sigma_{C_{H(Pan)}}\simeq 1.0$. Because the length of the hysteresis buffer must be an integer value, $\overline{C}_{H(Pan)}$, needed to be rounded off. Rounding to the nearest whole number initially seemed the most logical approach. Upon further consideration, however, it was decided to round 7.4 up to 8. Considering the relatively small data base (45 measurements) upon which the average was based, the fact that the standard deviation was 1.0 and that the gear backlash will only increase

with time, this seemed like the most reasonable approach. The buffer length for the Tilt axis was set equal to 6 ($\overline{C}_{H(Tilt)} = 6.06$) .

3. Implementing the Scale Factor

There are three counters in each MPU that keep track of the position information for the axis of interest. The first, BINCT, is simply a binary counter that is incremented by one for each valid CW count and decremented by one for each valid CCW count. The other two counters consist of two sets of pointers, two sets of data registers and a shared data table. Each byte in a pointer points to an address in the table that contains two BCD digits which make up a portion of the position information.

In order to increment (decrement) the pulse count, BCDCT, by one, the count pointer, CTPTR, is incremented (decremented) by one causing it to point to a new table address. The contents of the table at the new addresses are then moved into BCDCT. Modification of the position counter, DEGRES, is performed in much the same manner. DEGRES contains a BCD number that, when multiplied by 0.001, represents the angular position (in degrees) of the shaft of interest. Thus, each time the camera is displaced in a CW direction through one degree, the contents of DEGRES should be incremented by 1000. To do this, the position pointer, PTR, must be incremented (decremented) by seven or eight each time CTPTR is incremented (decremented) by one. Incrementing PTR by seven corresponds to an angular displacement of 0.007° and since $\overline{SF}_{Pan}$ and $\overline{SF}_{Tilt}$ are each slightly larger than 0.007°, periodically PTR must be incremented by eight to reduce the cumulative round off error. Specifically, if PTR is incremented by seven each time a valid CW pulse is detected (except when BINCT is an even multiple of 32) and is incremented by eight when BINCT is a modulo 32 number, the effective scale factor is given by:

$$\begin{aligned} SF_{eff_1} &= \frac{1}{32}(31(0.007) + 0.008) \\ &= 0.00703125°\text{Pulse}^{-1} \ , \end{aligned} \tag{28}$$

which is slightly larger than the desired 0.0070312°Pulse^{-1}, for the Pan axis and slightly smaller than the desired 0.0070452°Pulse^{-1} for the Tilt axis. To further reduce the cumulative round off on the Pan axis, every 16,384 ($2^{14} = 32 \times 512$) counts PTR is incremented by seven instead of eight. This results in an effective scale factor of,

$$SF_{eff_2} = \frac{1}{512}\left\{511\left[\frac{1}{32}(31(7)+8)\times 10^{-3}\right] + 0.007\right\}$$
$$= \left(7.03119 \times 10^{-3}\right)^{\circ}\text{Pulse}^{-1} \ , \tag{29}$$

which is within two parts in one million.

The maximum error introduced into the measurement should occur when the camera is rotated through the largest possible angle. To predict this error on the Pan axis, when the camera has been displaced by 360°,

$$\text{BCDCT} = \frac{360^{\circ}}{SF_{\text{Pan}}}$$
$$= 51{,}200 \text{ Pulses} \tag{30}$$

so the position error using SF_{eff_1} and SF_{eff_2} should be;

$$e_{\text{Pan}} = 360^{\circ} - [3(SF_{eff_2}) + (51{,}200 - 3(16{,}384))(S_{eff_1})]$$
$$= 0.00295^{\circ} \ . \tag{31}$$

Thus, the error due to the scale factor on the Pan axis should be well within the desired resolution of $\pm 0.006^{\circ}$.

Using SF_{eff_1} alone as the scale factor for the Tilt axis, the maximum theoretical error over $\pm 12^{\circ}$ due to the scale factor round off is determined in the same manner.

$$\text{BCDCT} = \frac{12^{\circ}}{SF_{\text{Tilt}}}$$
$$= 17{,}033 \text{ Pulses} \tag{32}$$

So that,

$$e_{\text{Tilt}} = 12^{\circ} - 17{,}033(SF_{eff_1})$$
$$= 0.0234^{\circ} \ , \tag{33}$$

which again is significantly less than the required resolution of $\pm 0.23^{\circ}$ for the Tilt axis.

The final step in the Count Routine is a branch to the Display Routine. Depending on whether the MPU is in the Count or Position Mode, the Display Routine copies the contents of BCDCT or DEGRES to the output ports and then executes an RTI instruction.

D. FINAL TESTING

1. General

Final laboratory testing and evaluation of the measurement system was performed after the calibration results had been implemented in each of the MPU Count Routines. The purpose of the testing was to verify that the calibration results had been properly coded into the MPU's and to determine the resolution capabilities of the measurement system experimentally.

This verification process included determining the combined error due to the hysteresis and scale factor errors. The use of some simple multiple random variable theory was therefore required. From [Ref. 20: pp. 121,122] the variance of a weighted sum of M random variables is the weighted sum of their covariances, $C_{X_iX_j}$, and is given by,

$$\sigma^2 = \sum_{i=1}^{M}\sum_{j=1}^{M}\alpha_i\alpha_j C_{X_iX_j} \ , \tag{34}$$

where α_i is the weight associated with X_i. Additionally, the covariance can be expressed as

$$C_{XY} = \rho\sigma_X\sigma_Y \ , \tag{35}$$

where ρ is the normalized second-order moment and is known as the correlation coefficient of X and Y. The correlation coefficient is bounded by

$$-1 \leq \rho \leq 1 \ . \tag{36}$$

In the case where there are two equally weighted random variables, $M = 2$ and $\alpha_i = \alpha_j = 1.0$. Substituting into Equation (34) and expanding

$$\sigma^2 = C_{XX} + C_{XY} + C_{YX} + C_{YY} \ . \tag{37}$$

Using Equation (35),

$$\sigma^2 = \sigma_X^2 + 2\rho\sigma_X\sigma_Y + \sigma_Y^2 \ . \tag{38}$$

Combining (36) and (38) yields

$$\sigma_X^2 - 2\sigma_X\sigma_Y + \sigma_Y^2 \leq \sigma^2 \leq \sigma_X^2 + 2\sigma_X\sigma_Y + \sigma_Y^2 \ . \tag{39}$$

The bounds of the combined scale factor and hysteresis errors can therefore be determined from

$$\sqrt{\sigma_{e_{SF}}^2 - 2\sigma_{e_{SF}}\sigma_{e_H} + \sigma_{e_H}^2} \leq \sigma_e \leq \sqrt{\sigma_{e_{SF}}^2 + 2\sigma_{e_{SF}}\sigma_{e_H} + \sigma_{e_H}^2} \quad . \tag{40}$$

where:

- σ_e = standard deviation of the combined error,
- $\sigma_{e_{SF}}$ = standard deviation of the scale factor error, and
- σ_{e_H} = standard deviation of the hysteresis error.

Note that the bounds are determined by the two cases where the hysteresis error, e_H, and the scale factor error, e_{SF}, are "completely correlated". The upper bound corresponds to the case where an increase in e_{SF} implies an increase in e_H, and the lower bound corresponds to the case where an increase in e_{SF} directly implies a decrease in e_H.

A third case is also of particular interest. If e_H and e_{SF} are completely uncorrelated, i.e., $\rho = 0$, then from Equation (38),

$$\sigma_e = \sqrt{\sigma_{e_{SF}}^2 + \sigma_{e_H}^2} \quad , \tag{41}$$

which can also be written as

$$e = \pm \sqrt{e_{SF}^2 + e_H^2} \quad , \tag{42}$$

where $e = \pm \sigma_e$ is the 1.0 σ error due to the scale factor and hysteresis errors, e_{SF} and e_H respectively. Based on the physical nature of the two errors it is reasonable to assume that e_{SF} and e_H are statistically uncorrelated; however, no experimental data was collected to support this hypothesis. Due to this lack of a priori information, the maximum RMS error, $e_{max} = \pm \sigma_{e_{max}}$, given by

$$e_{max} = \pm \sqrt{e_{SF}^2 + 2e_{SF}e_H + e_H^2} \quad , \tag{43}$$

will be used to describe the resolution capabilities of the measurement system.

2. Pan Axis

a. Hysteresis

To test the operation of the Pan axis hysteresis buffer, the Initialization Routine was programmed to set the buffer length to 8. Then, as described in the first section of this chapter, the servo was used to position the beam of a small laser on a fixed target. By approaching the target alternately from a CW and a CCW direction and

comparing the difference in the output counts from the shaft encoders, the hysteresis error was determined. The average error after 31 measurements was

$$\bar{e}_{H(Pan)} = -0.1880 \text{ Pulses} , \tag{44}$$

and the RMS error was

$$\sigma_{e_{H(Pan)}} = 1.7699 \text{ Pulses} . \tag{45}$$

Since the mean error is "near zero" compared to the standard deviation, the 1.0 σ error e_H, due to the hysteresis can be determined from

$$e_H = \pm (\sigma_{e_H})\overline{SF} \tag{46}$$

so that

$$e_{H(Pan)} = \pm 0.0124^\circ . \tag{47}$$

b. Scale Factor

Verification of the scale factor was performed in the same manner as the scale factor calibration, except that the MPU was calibrated in the Count Mode and tested in the Position Mode. Since these tests sought to find the maximum error due to the scale factor, and the error is directly proportional to the angle that is being measured, these tests were conducted by displacing the camera servo through the maximum angles permitted by the camera and the laboratory. Specifically, on the Pan axis the servo was rotated through approximately 360°. The mean error due to the scale factor on the Pan axis was determined from 15 samples to be

$$\bar{e}_{SF(Pan)} = -0.0018^\circ \tag{48}$$

and the RMS error was

$$\sigma_{e_{SF(Pan)}} = 0.00890^\circ . \tag{49}$$

As with the hysteresis error, if we neglect the small bias due to the $\bar{e}_{SF(Pan)}$, we can describe the 1.0 σ RMS error due to the scale factor as

$$\begin{aligned} e_{SF(Pan)} &= \pm \sigma_{SF(Pan)} \\ &= \pm 0.00890^\circ \end{aligned} . \tag{50}$$

c. Combined Error

From Equation (42) the combined error on the Pan axis if e_H and e_{SF} are uncorrelated can be estimated as

$$\begin{aligned} e_{Pan} &= \pm \sqrt{(0.0124)^2 + (0.0089)^2} \\ &= \pm 0.01526^\circ \ . \end{aligned} \tag{51}$$

And from Equation (43) the maximum combined error on the Pan axis is

$$e_{Pan_{max}} = \pm \sqrt{(0.0124)^2 + 2(0.0124)(0.0089) + (0.0089)^2} \tag{52}$$

$$e_{Pan_{max}} = \pm 0.0213^\circ \ . \tag{53}$$

The combined error is approximately three times larger than the design specification limit and is due primarily to the hysteresis error.

3. Tilt Axis

a. Hysteresis

The procedure used to verify the operation of the calibrated Tilt MPU was identical to that described in the previous section. Using a hysteresis buffer length of 6 resulted in

$$\bar{e}_{H(Tilt)} = -0.0965 \text{ Pulses} \tag{54}$$

and,

$$\sigma_{e_{H(Tilt)}} = 1.3156 \text{ Pulses} \tag{55}$$

after 13 samples. As before we can define the 1.0 σ error from $e = \sigma\overline{SF}$ to be

$$e_{H_{Tilt}} = \pm 0.00529^\circ \ . \tag{56}$$

b. Scale Factor

Testing the scale factor on the Tilt axis was limited by the physical construction of the servo and the size of the laboratory. The angle over which testing could be performed was limited to $\pm 6^\circ$ from the horizontal plane. Consequently, the RMS error for the scale factor on the Tilt axis was determined in exactly the same manner as

the RMS error for the Pan axis scale factor, but since the error due to rounding of the scale factor is directly proportional to the angle being measured the results were multiplied by 2.0 to account for the limited range of the test. The modified results should therefore be representative of the maximum error one should expect if the measurement system is used to measure elevation angles over a range of $\pm 12°$.

The error due to the scale factor is described from 16 samples by

$$\bar{e}_{SF(Tilt)} = 0.0070° \tag{57}$$

and,

$$\sigma_{e_{SF(Tilt)}} = 0.0665° \ . \tag{58}$$

Including the factor of two in the calculation we have

$$\begin{aligned} e_{SF(Tilt)} &= \pm 2(0.0665°) \\ &= \pm 0.1330° \ . \end{aligned} \tag{59}$$

c. Combined Error

The combined RMS error is determined in the same manner as before. If e_H and e_{SF} are uncorrelated,

$$\begin{aligned} e_{Tilt} &= \pm \sqrt{(0.1330)^2 + (0.00529)^2} \\ &= 0.1331° \ , \end{aligned} \tag{60}$$

and the maximum combined RMS error is

$$e_{Tilt_{max}} = \pm \sqrt{(0.1330)^2 + 2(0.1330)(0.00529) + (0.00529)^2} \tag{61}$$

$$e_{Tilt_{max}} = \pm 0.1383° \ . \tag{62}$$

The Tilt axis measurement system appears to perform well within the required resolution specifications.

E. FINAL IMPLEMENTATION

Once the program debugging, calibration and testing were completed, final implementation of the system remained. Taking the design from the prototype/development model to a fully functional system was a straightforward but time-consuming evolution.

The plans for the printed circuit boards (PCB's) were made directly from the schematics shown in Appendix A; the boards were then etched and assembled from the plans which are shown in Appendix B. All of this work was performed by sailors attached to the Academic Division of the NPS.

As previously discussed, the M68705EVM Evaluation Module provided a powerful and flexible means of debugging and evaluating the performance of the microprocessor based signal conditioner. Additionally, once program testing was completed the EVM's EPROM microprocessor programmer provided the means to program the EPROM MCU's. A detailed, but simple to follow, programming procedure for programming the MC68705U3 is given in [Ref. 18: pp. (3-26)-(3-27)].

V. CONCLUSIONS AND RECOMMENDATIONS

A. SYSTEM PERFORMANCE

The prototype system was calibrated and successfully tested in a laboratory environment. Experimental results indicate that the system is capable of measuring the video camera's elevation over a range of $\pm 12°$ with a resolution of $\pm 0.138°$ and its azimuth over 360° with a resolution of $\pm 0.021°$. The system was designed to be low cost, reliable, and easy to operate. Only time will tell whether these objectives were truly achieved.

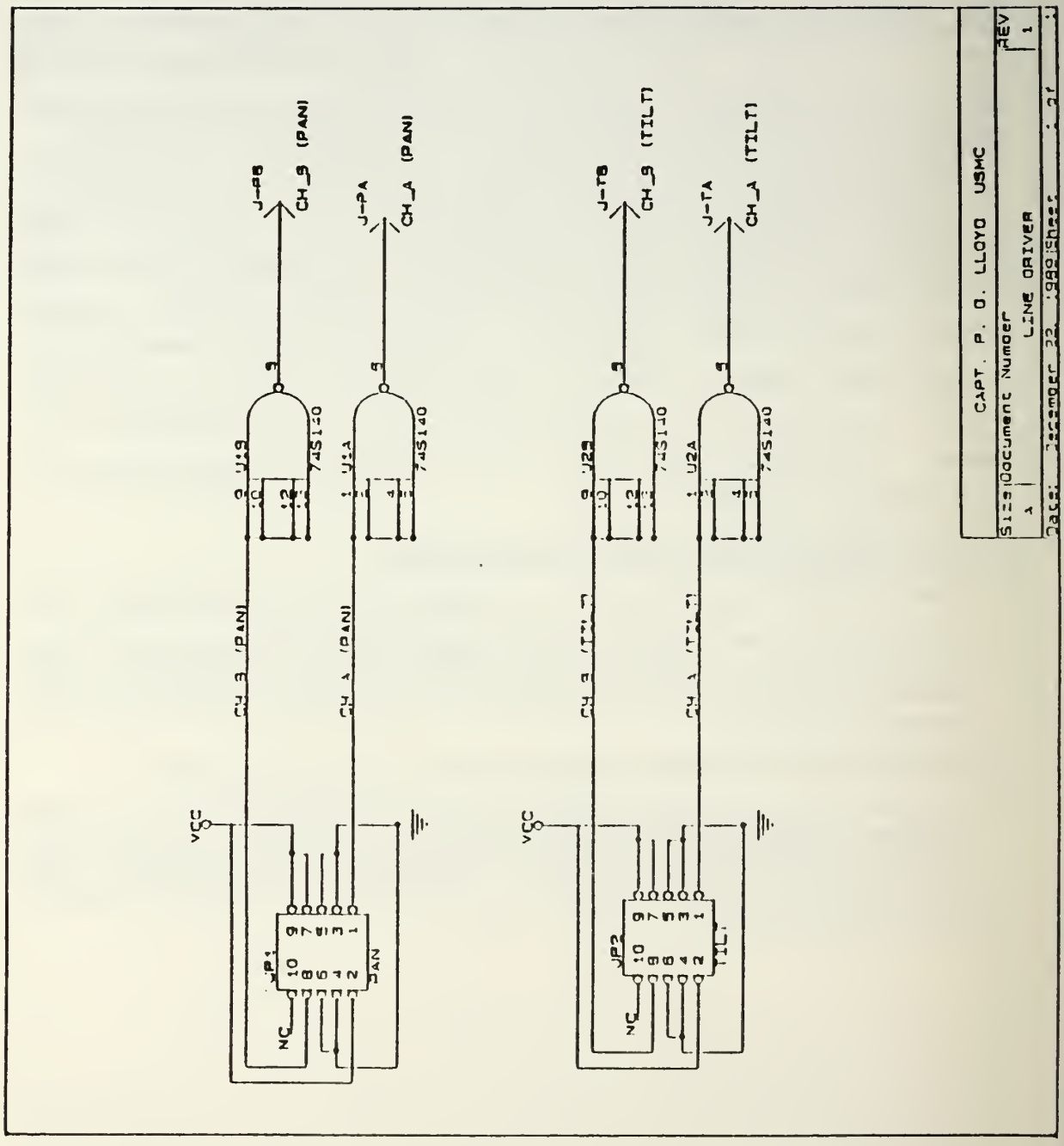
The portion of the system that will be located outdoors has been weatherproofed and is ready to be placed in service. Printed circuit board plans for the remainder of the system have been developed, but final implementation of the system is still ongoing. Once the system is fully operation additional testing should be performed in order to verify the completed system's performance. Although the laboratory results indicate that the system is capable of meeting all of the design criteria except for the required resolution on the Pan axis, the system must be further tested in a non-laboratory environment. "...The proof of a good design rests in the ability of the system to function in the outside world." [Ref 21]

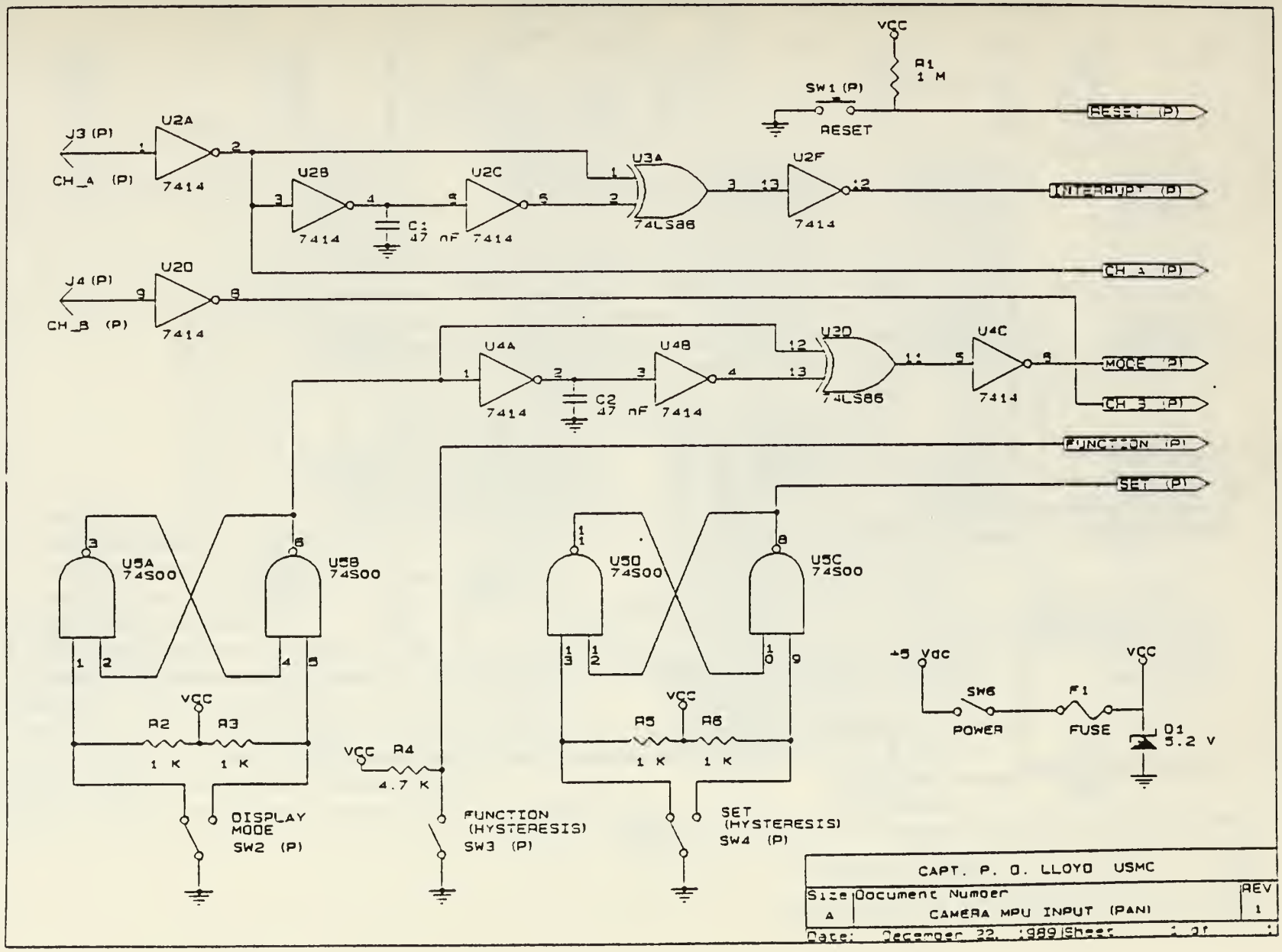
B. RECOMMENDATIONS FOR FURTHER WORK

There are several areas for follow-on work with this project. Some possibilities are:

- Incorporate the measurement system's output into the video image being created by the video camera. This would permit a permanent record of the position information to be stored with the video image and would facilitate identification of the image at a later date.
- Design and build an automatic feedback control system for the camera.
- Implementation of a second video camera at the NPS, together with the NPS modified IRSTD, would permit triangulation of a target and would consequently provide range information which is not currently available. This information could provide valuable additional information to those who are developing the signal processing algorithms.

APPENDIX A. SCHEMATIC DIAGRAMS

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R1
1 M
SW1 (P)
RESET
RESET (P)
J3 (P)
CH_A (P)
U2A
7414
U2B
7414
C1
47 nF
U2C
7414
U3A
74LS86
U2F
7414
INTERRUPT (P)
CH_A (P)
J4 (P)
CH_B (P)
U2D
7414
U4A
7414
C2
47 nF
U4B
7414
U3D
74LS86
U4C
7414
MODE (P)
CH_B (P)
FUNCTION (P)
SET (P)
U5A
74S00
U5B
74S00
U5D
74S00
U5C
74S00
VCC
R2
R3
1 K
1 K
DISPLAY
MODE
SW2 (P)
VCC
R4
4.7 K
FUNCTION
(HYSTERESIS)
SW3 (P)
VCC
R5
R6
1 K
1 K
SET
(HYSTERESIS)
SW4 (P)
+5 Vdc
SW6
POWER
F1
FUSE
VCC
D1
5.2 V
CAPT. P. D. LLOYD USMC
Size
A
Document Number
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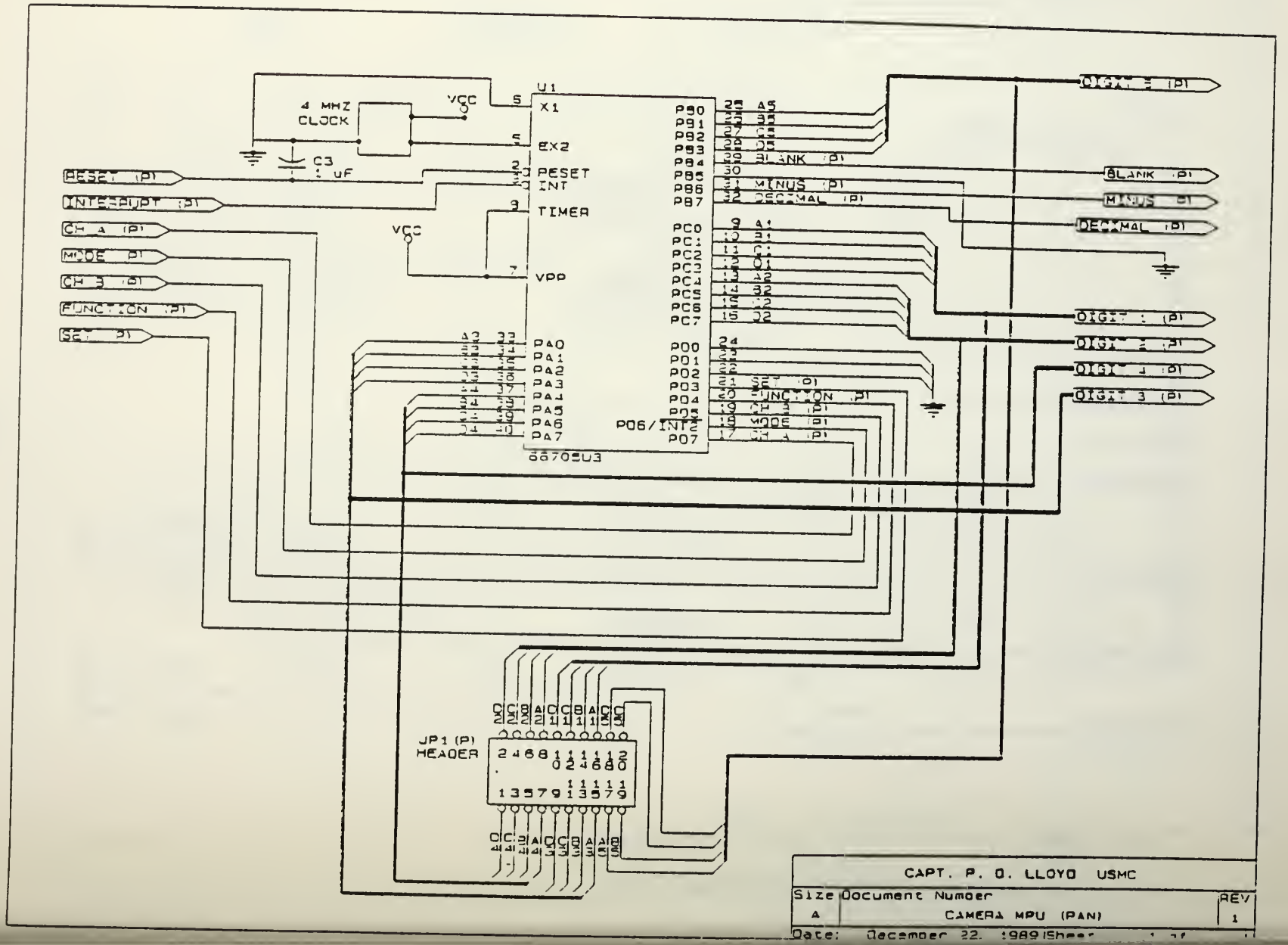
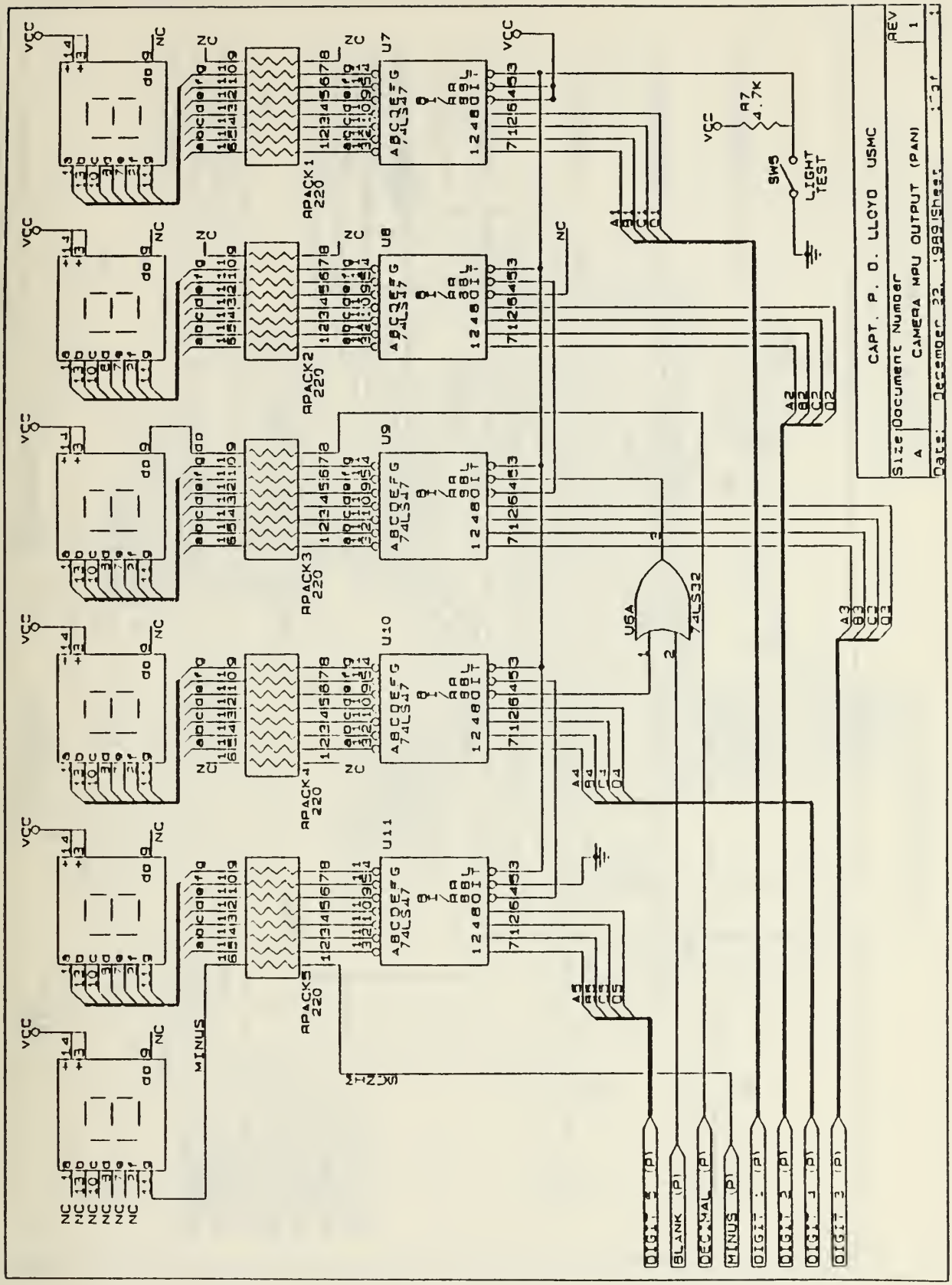
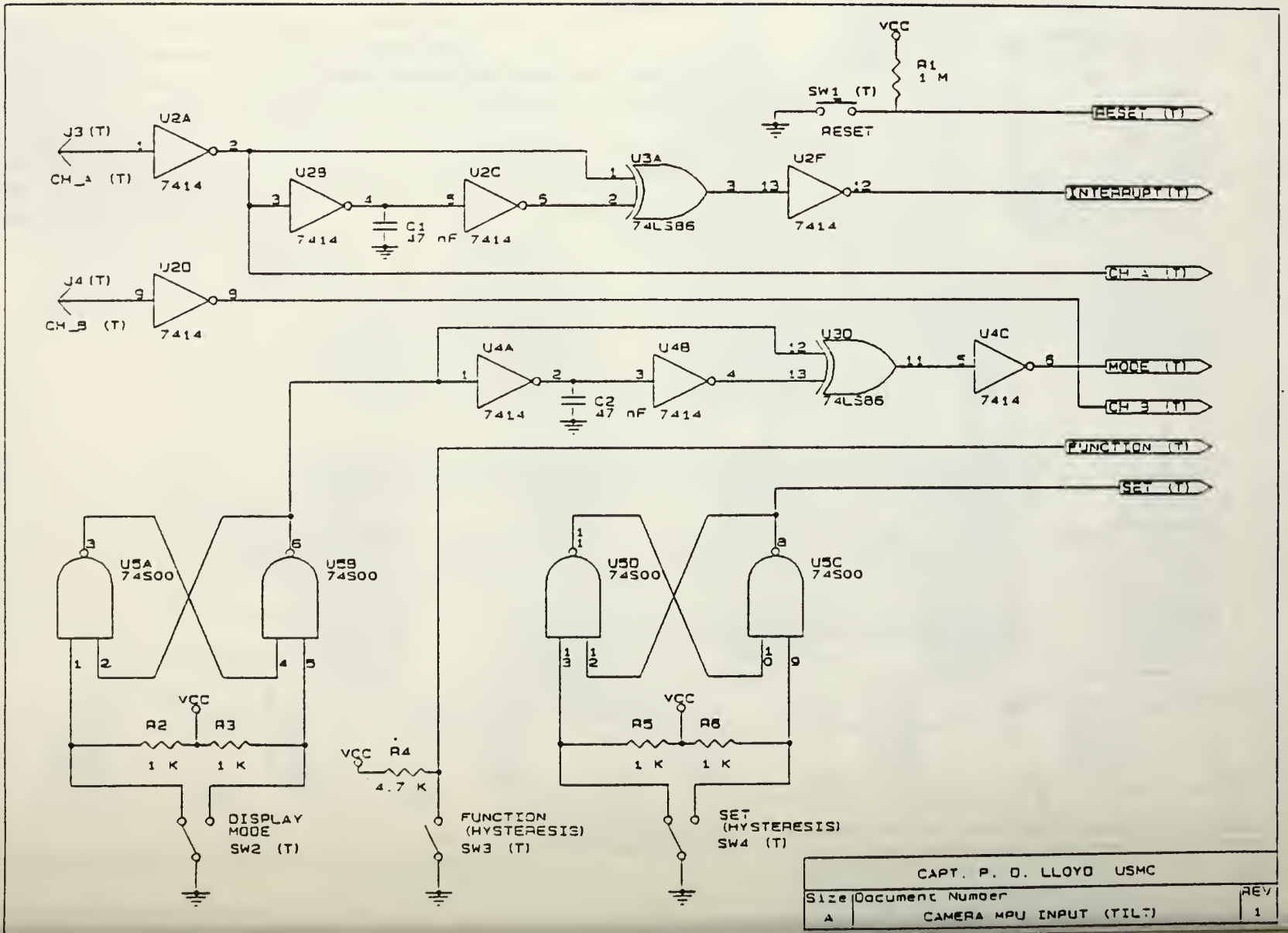
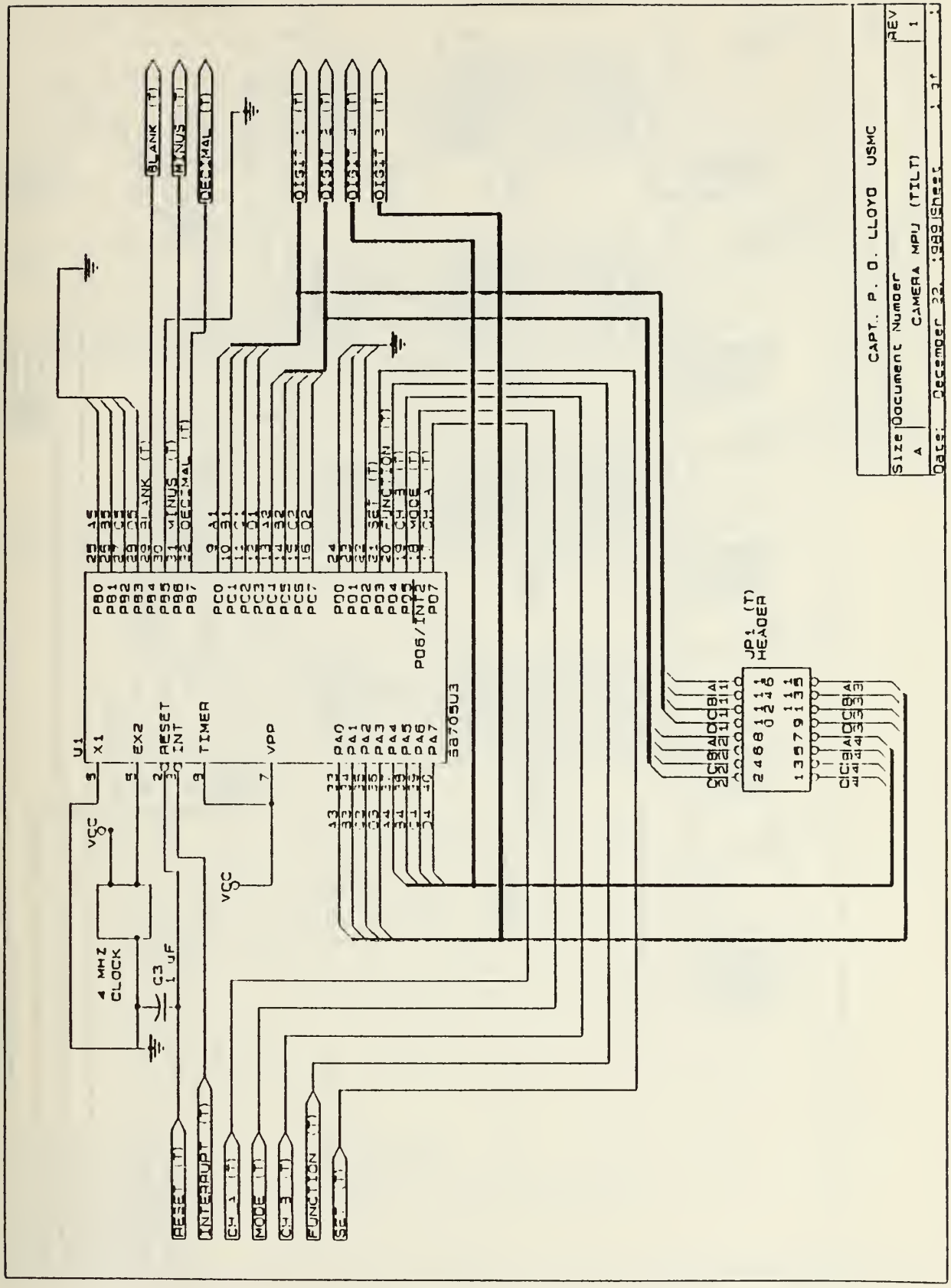
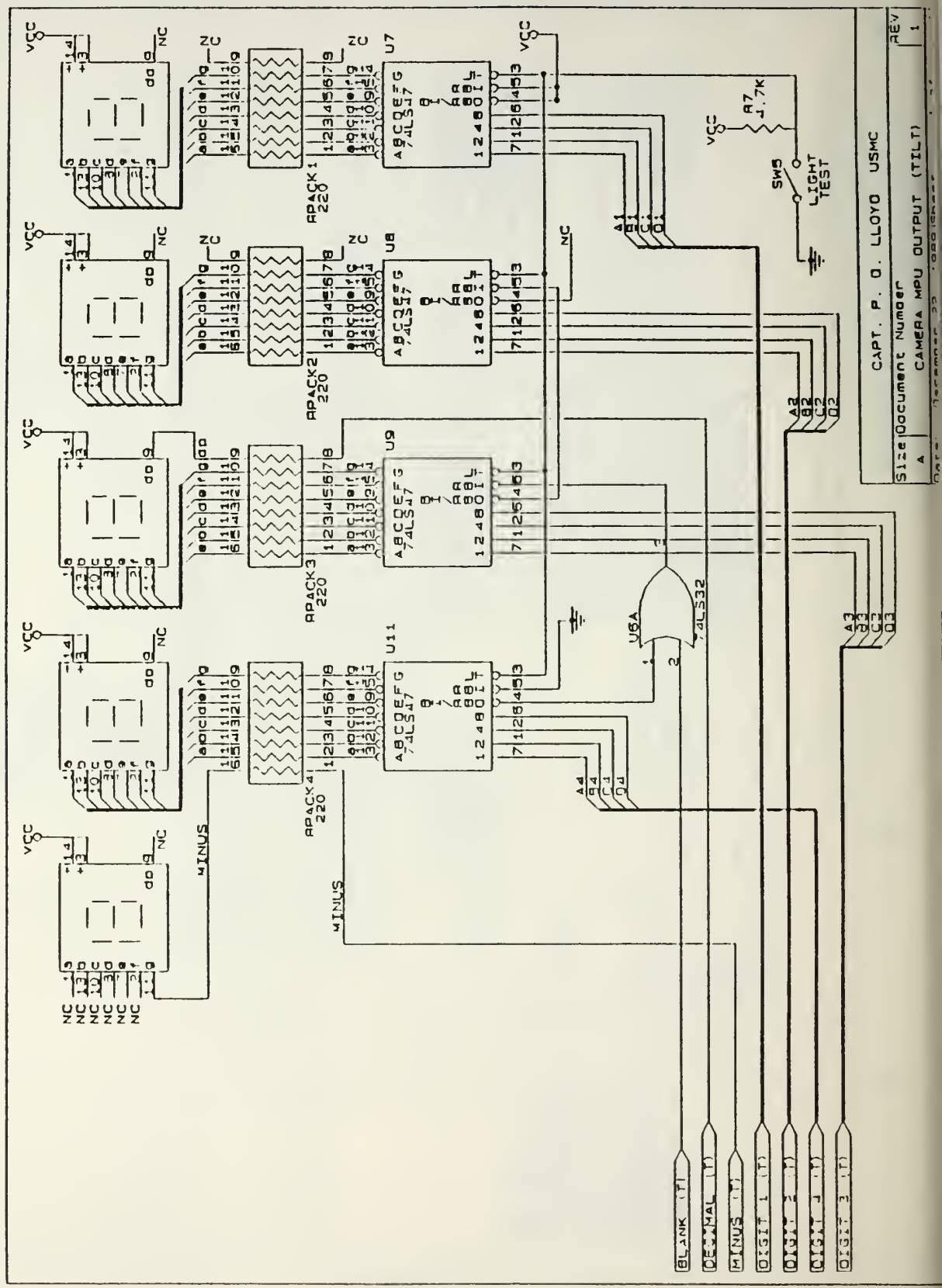
REV
1
Date: December 22, 1989 Sheet of

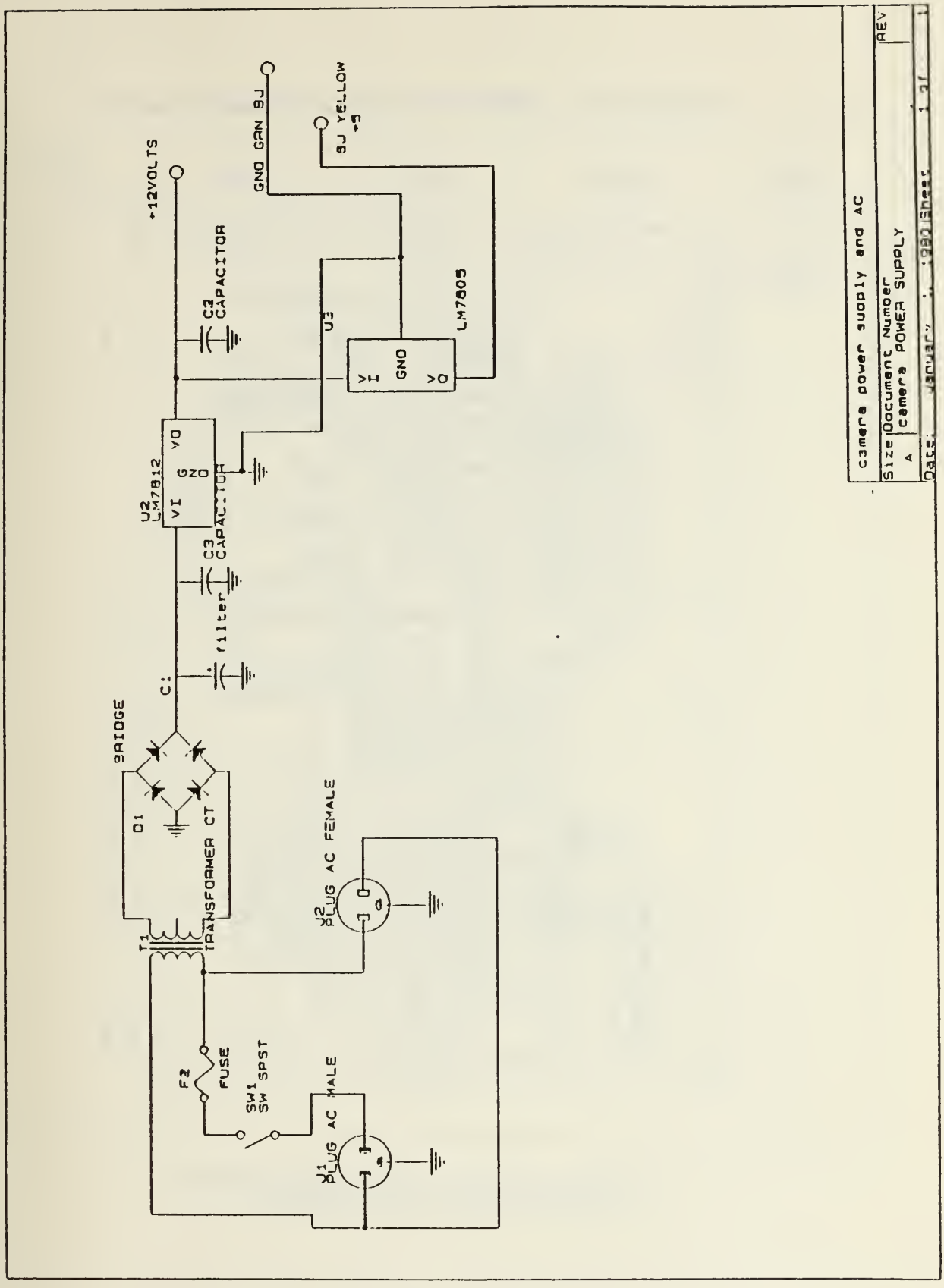

4 MHZ
CLOCK
VCC
U1
X1
EX2
C3
.1 uF
RESET (P)
INTERRUPT (P)
CH A (P)
MODE (P)
CH B (P)
FUNCTION (P)
SET (P)
RESET
INT
TIMER
VPP
PA0
PA1
PA2
PA3
PA4
PA5
PA6
PA7
P06/INT2
P07
P90
P91
P92
P93
P94
P95
P96
P97
BLANK (P)
MINUS (P)
DECIMAL (P)
PC0
PC1
PC2
PC3
PC4
PC5
PC6
PC7
P00
P01
P02
P03
P04
P05
P06
P07
FUNCTION (P)
MODE (P)
CH A (P)
DIGIT 3 (P)
DIGIT 2 (P)
DIGIT 1 (P)
DIGIT 0 (P)
8870EU3
JP1 (P)
HEADER
2 4 6 8 1 1 1 1 1 2
0 2 4 6 8 0
1 3 5 7 9 1 1 1 1 1
1 3 5 7 9
CAPT. P. O. LLOYD USMC
Size
A
Document Number
CAMERA MPU (PAN)
REV
1
Date: December 22, 1989 Sheet


CAPT. P. D. LLOYD USMC
Size Document Number REV
A CAMERA MPU OUTPUT (PAN) 1
Date: December 22, 1989 Sheet
LIGHT TEST
SW5
R7 4.7K
VCC
RPACK1 220
RPACK2 220
RPACK3 220
RPACK4 220
RPACK5 220
U7
U8
U9
U10
U11
74LS47
74LS32
U5A
MINUS
BLANK (P)
DECIMAL (P)
MINUS (P)
NC

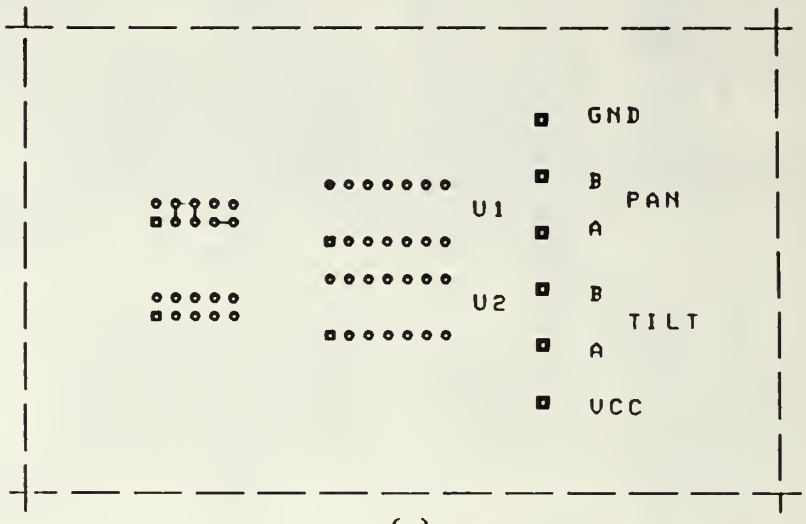

VCC
R1
1 M
SW1 (T)
RESET
RESET (T)
U3 (T)
CH_A (T)
U2A
7414
U2B
U2C
C1
47 nF
U3A
74LS86
U2F
INTERRUPT (T)
CH_A (T)
U4 (T)
CH_B (T)
U20
U4A
U4B
C2
47 nF
U30
U4C
MODE (T)
CH_B (T)
FUNCTION (T)
SET (T)
U5A
74S00
U5B
U5D
U5C
R2
R3
1 K
R4
4.7 K
R5
R6
DISPLAY
MODE
SW2 (T)
FUNCTION
(HYSTERESIS)
SW3 (T)
SET
(HYSTERESIS)
SW4 (T)
CAPT. P. D. LLOYD USMC
Size
A
Document Number
CAMERA MPU INPUT (TILT)
REV
1


CAPT. P. D. LLOYD USMC
Size
Document Number
REV
CAMERA MPU (TILT)
Date: December 22, 1989 Sheet
U1
8A705U3
4 MHZ CLOCK
C3
1 uF
VCC
JP1 (T)
HEADER
BLANK (T)
MINUS (T)
DECIMAL (T)
RESET (T)
INTERRUPT (T)
MODE (T)
FUNCTION (T)

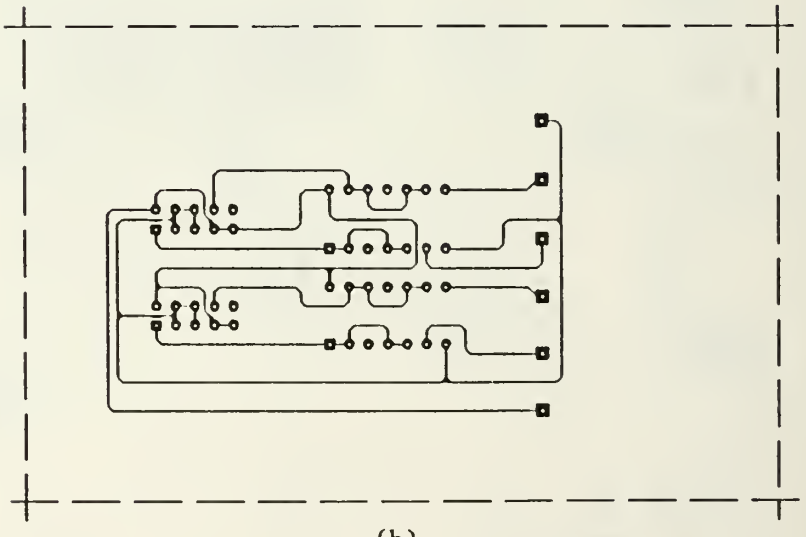

CAPT. P. D. LLOYD USMC
CAMERA MPU OUTPUT (TILT)
Size
Document Number
A
REV
1
VCC
NC
GND
RPACK1
220
RPACK2
220
RPACK3
220
RPACK4
220
U7
U8
U9
U11
U6A
74LS32
R7
4.7K
SW5
LIGHT
TEST
MINUS
A1
B1
C1
D1
A2
B2
C2
D2
A3
B3
C3
D3
A4
B4
C4
D4
BLANK (T)
DECIMAL (T)
MINUS (T)
DIGIT 1 (T)
DIGIT 2 (T)
DIGIT 3 (T)
DIGIT 4 (T)


camera power supply and AC
Size
A
Document Number
camera POWER SUPPLY
REV
+12VOLTS
GND GRN BJ
BJ YELLOW
+5
C2
CAPACITOR
U3
LM7805
GND
VI
VO
U2
LM7812
VI
VO
GND
C3
CAPACITOR
filter
C1
BRIDGE
D1
TRANSFORMER CT
T1
J2
PLUG AC FEMALE
F2
FUSE
SW1
SW SPST
J1
PLUG AC MALE

APPENDIX B. PRINTED CIRCUIT BOARD PLANS

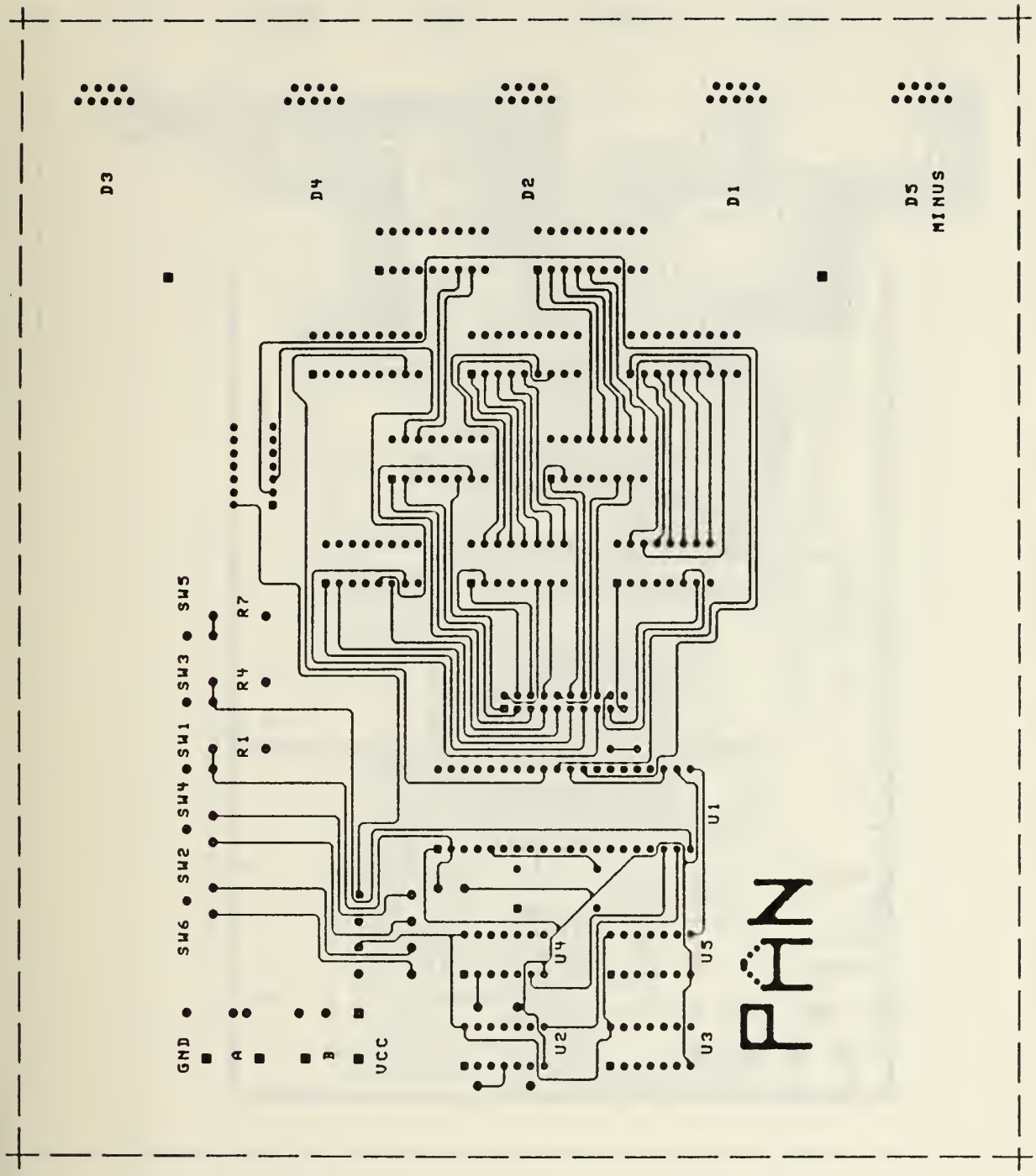


(a)

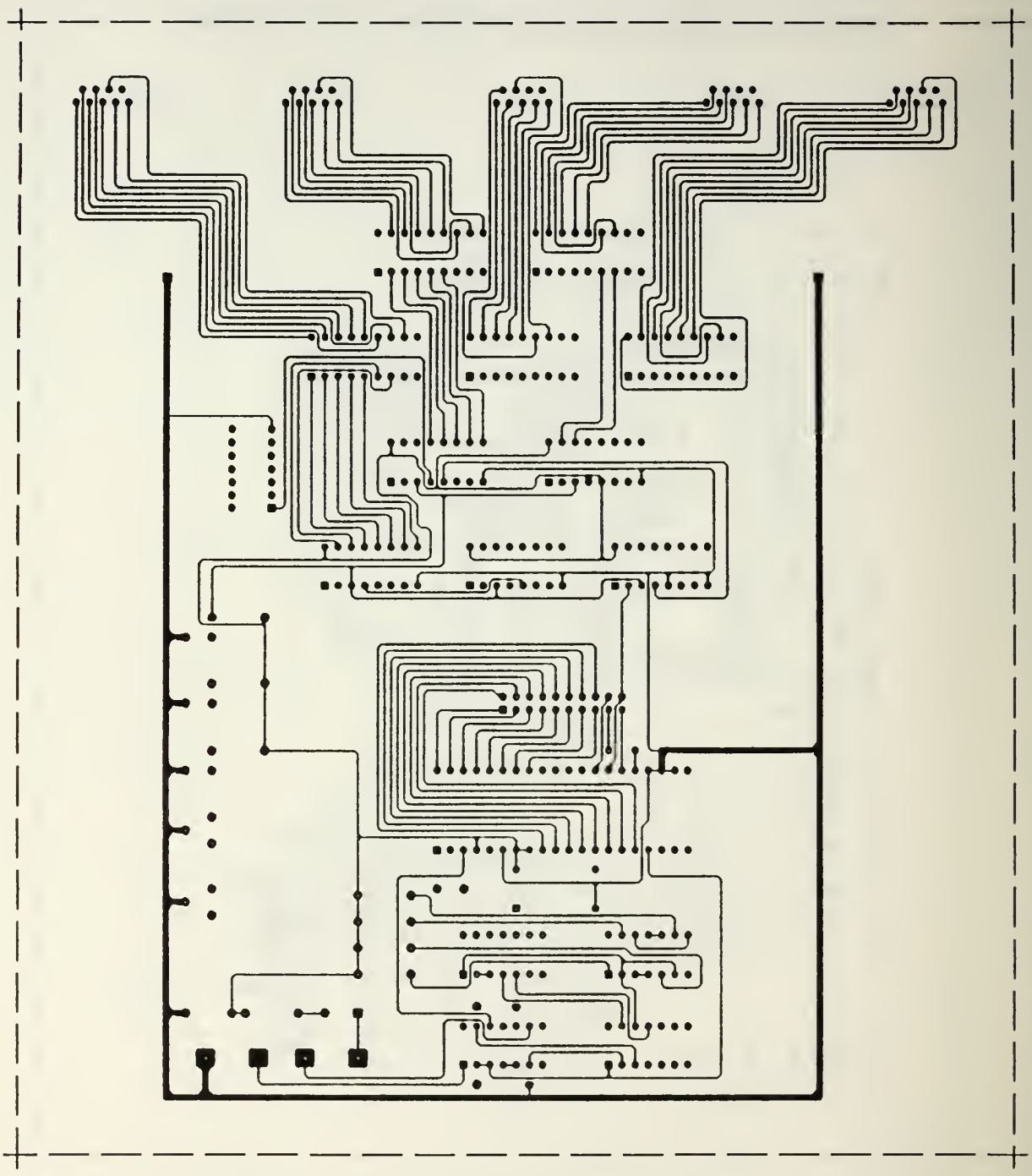


(b)

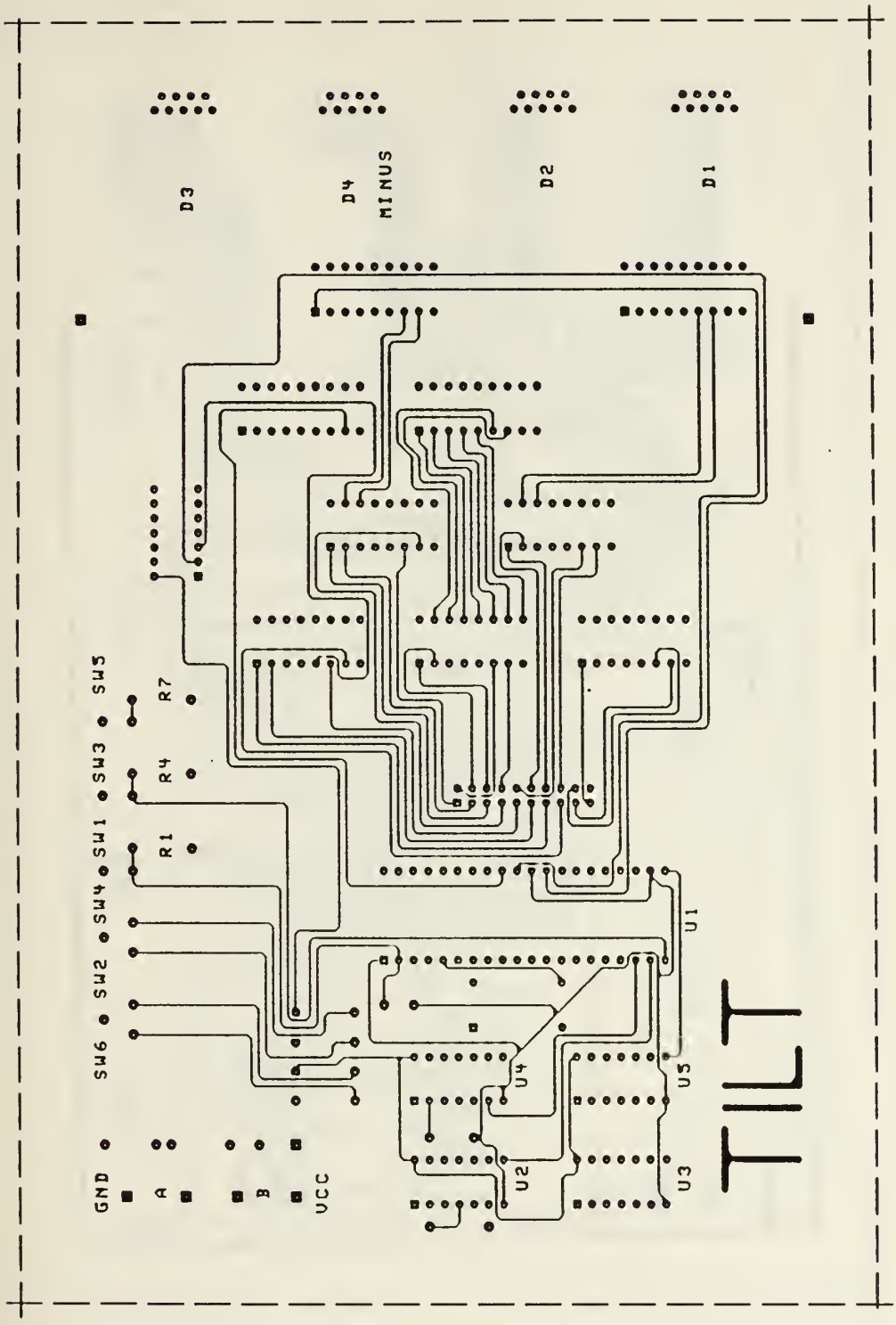
Line Driver, (a) Front and (b) Back. Full scale.



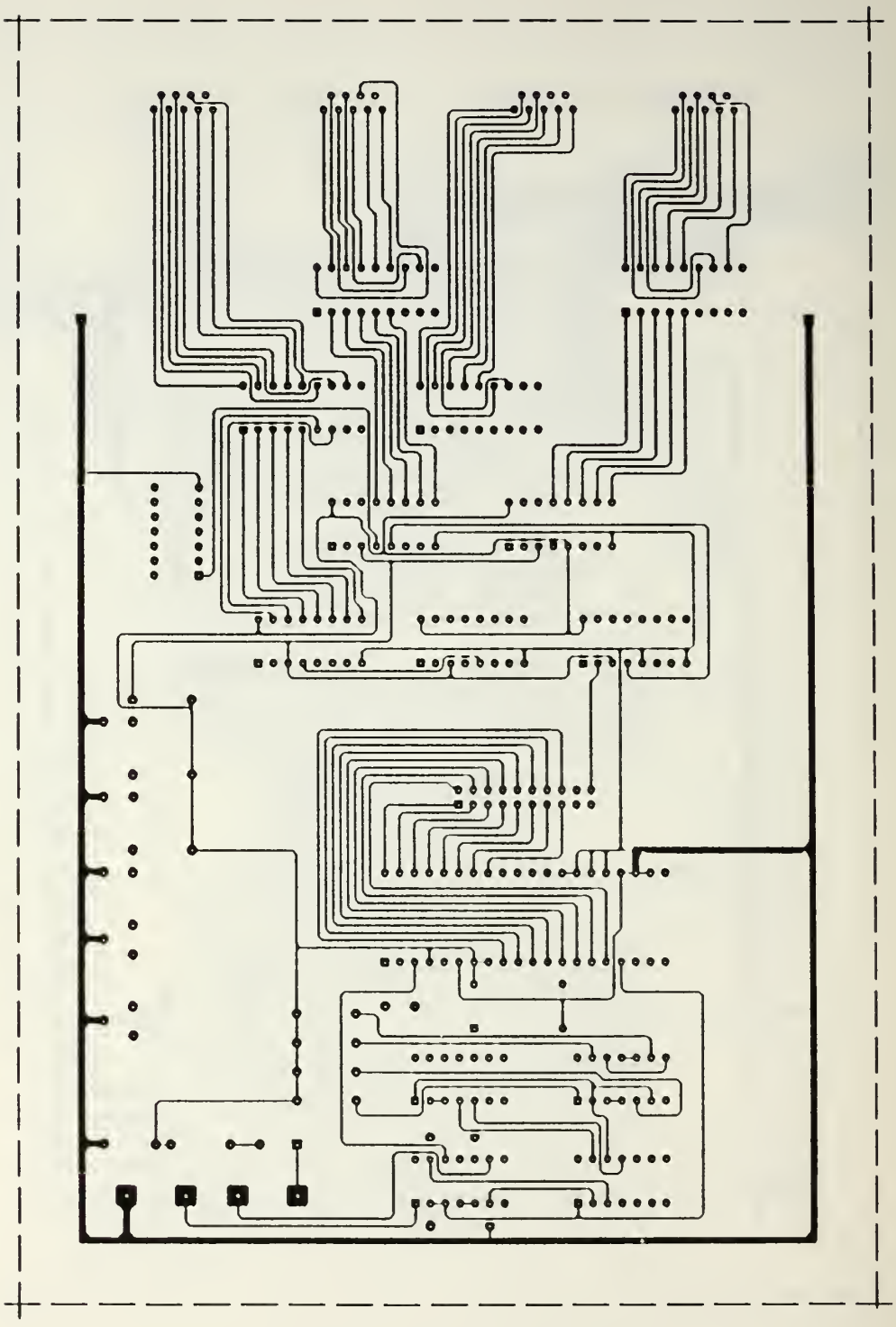
Pan MPU, Front. 90 % of full scale.



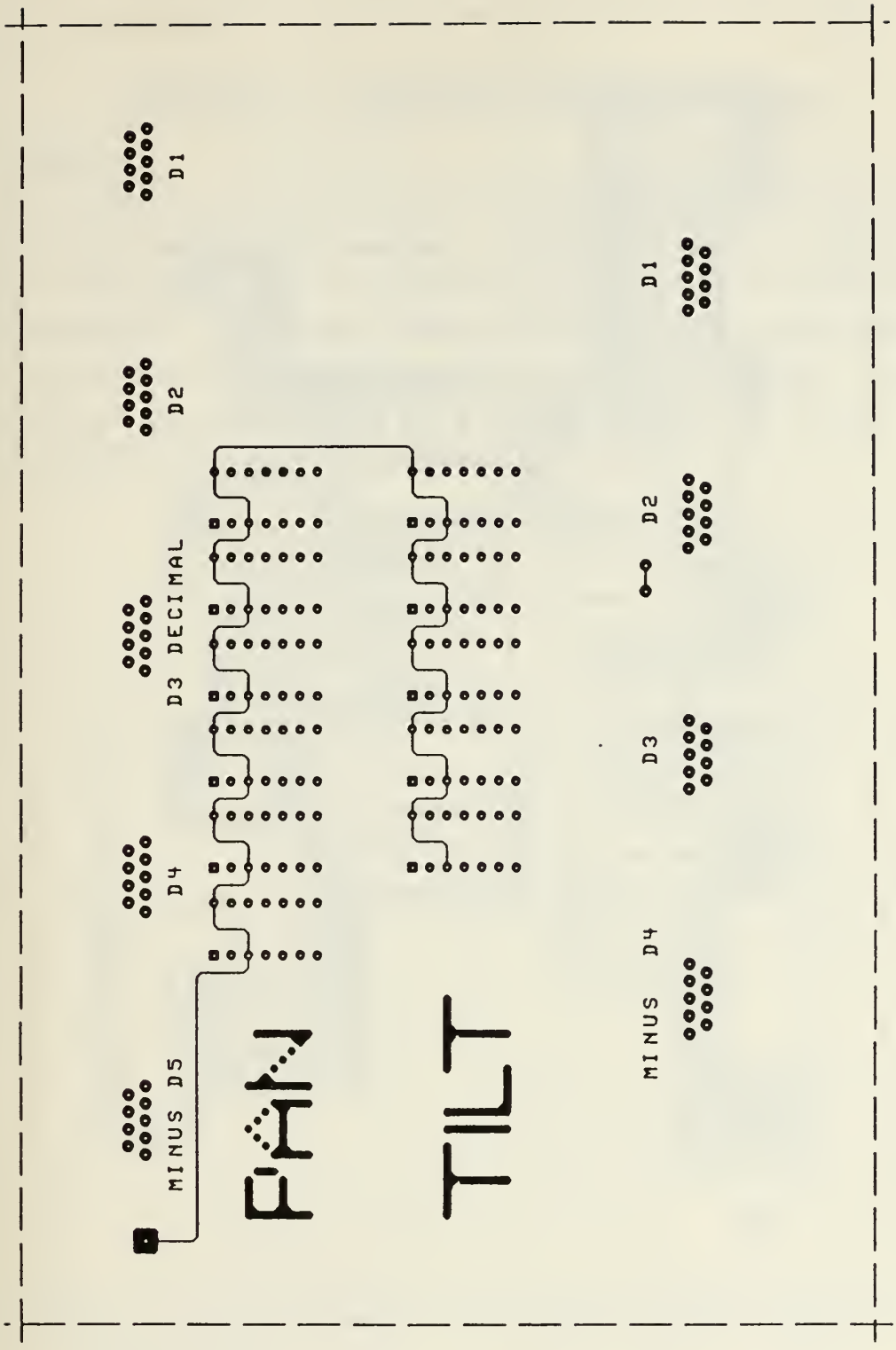
Pan MPU, Back. 90 % of full scale.



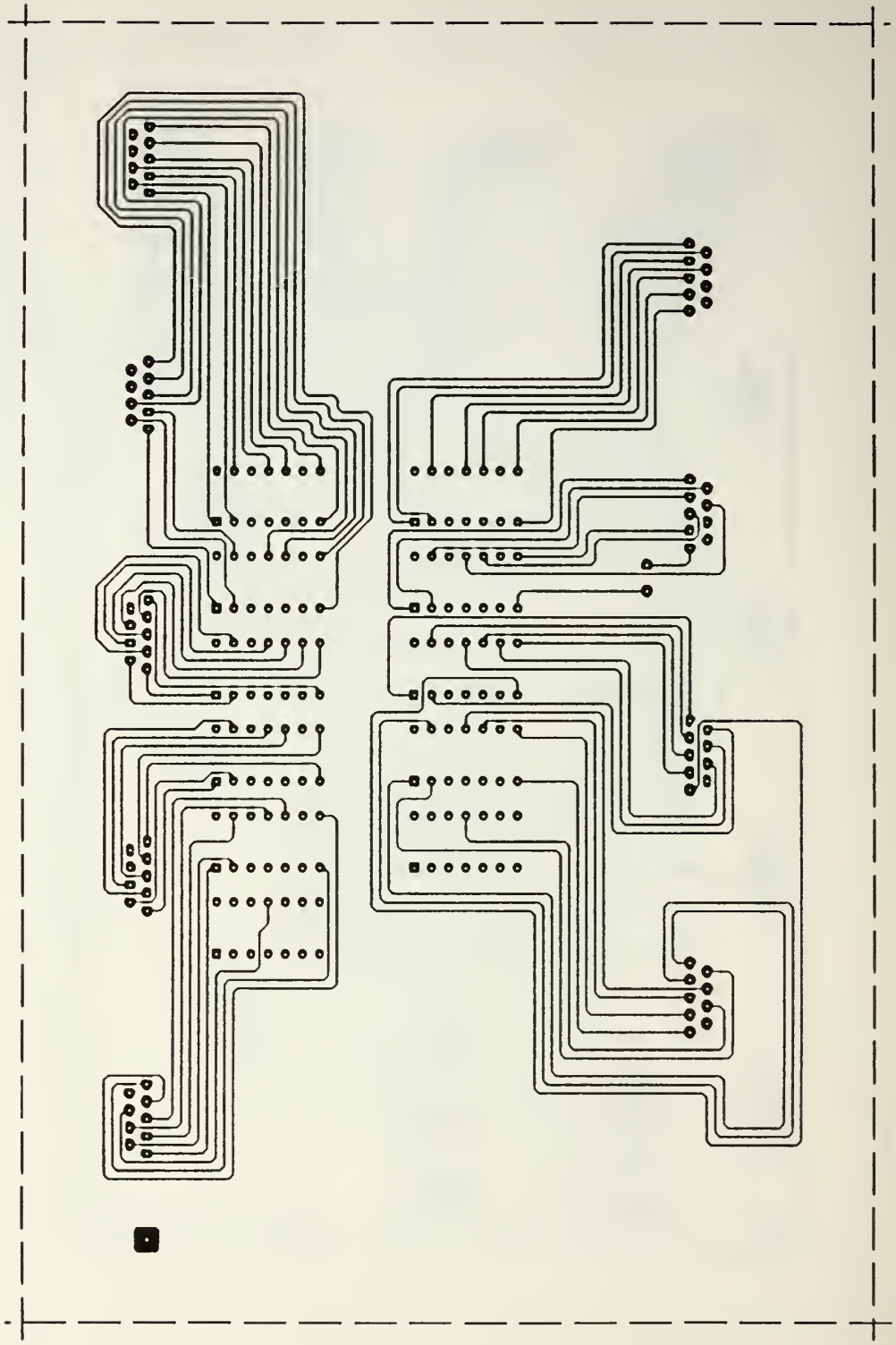
Tilt MPU, Front. 85 % of full scale.



Tilt MPU, Back. 85 % of full scale.



Display, Front. Full scale.



Display, Back. Full scale.

APPENDIX C. MICROPROCESSOR PROGRAMS

A. GENERAL

Sections B and C of this Appendix are the listing files for the two MPU programs written for the signal processor subsystems. The theory of operation of the two programs is identical and is most clearly described by Figure 31. The detailed operation of the Initialization , Mode Change, Blink, Output Display and Hysteresis Modify routines is described by the comments which accompany each of the programs. In addition to the detailed description provided by the program comments, the operation of the Count Routine is also explained in Chapter IV.

B. PAN

```
                        TTL             POSITION DETERMINING PROGRAM (AZIMUTH)
                *                       LATEST REVISION              9 MAY 89
                *                       FILE NAME                    PAN.ASM
                **
                ** PROGRAM DESCRIPTION
                **
                **
                **
                ** I/O REGISTER ADDRESSES
                **
0000            PORTA   EQU     $0000   I/O PORT A
0001            PORTB   EQU     $0001   I/O PORT B
0002            PORTC   EQU     $0002   I/O PORT C
0003            PORTD   EQU     $0003   INPUT PORT D
                **
                ** DATA DIRECTION REGISTER OFFSET
                **
0004            DDR     EQU     4       (eg. DDR FOR PORT A IS  PORTA+DDR )
                **
                ** OTHERS
                **
0008            TIMER   EQU     $0008   EIGHT BIT TIMER REGISTER.
0009            TCR     EQU     $0009   TIMER CONTROL REGISTER.
000A            MR      EQU     $000A   MISCELLANEOUS REGISTER.
0010            RAM     EQU     $0010   START OF ON-CHIP RAM(112 - 31 FOR STACK)
0080            ZROM    EQU     $0080   PAGE ZERO OF ROM.
0100            ROM     EQU     $0100   START OF MAIN ROM.
0F38            MOR     EQU     $0F38   MASK OPTION REGISTER.
0FF8            INTRPT  EQU     $0FF8   LOCATION OF INTERRUPT VECTORS.
1000            MEMSIZ  EQU     $1000   MEMORY ADDRESS SIZE.
                **
                ** EQUATES
                **
0001            BIT0    EQU     1
0002            BIT1    EQU     2
0004            BIT2    EQU     4
0008            BIT3    EQU     8
0010            BIT4    EQU     16
0020            BIT5    EQU     32
0040            BIT6    EQU     64
0080            BIT7    EQU     128
                **
0000            B0      EQU     0
0001            B1      EQU     1
0002            B2      EQU     2
0003            B3      EQU     3
0004            B4      EQU     4
0005            B5      EQU     5
0006            B6      EQU     6
0007            B7      EQU     7
                **
                ** EQUATES FOR THE TIMER CONTROL REGISTER
                **
                ***
0007            TIR     EQU     7       TIMER INTERRUPT REQUEST. 1 = REQUEST, 0 = NO REQ.
0006            TIM     EQU     6       TIMER INTERRUPT MASK. 1 = DISABLED, 0 = ENABLED.
0005            TIN     EQU     5       EXTERNAL OR INTERNAL CLOCK SOURCE. 1 = EXT, 0 = INT
0004            TEE     EQU     4       EXTERNAL CLOCK ENABLE. NOT USED.
0003            PSC     EQU     3       PRESCALER CLEAR. NOT USED.
0002            PS2     EQU     2       (PS2)  --
0001            PS1     EQU     1       (PS1)    |--  PRESCALER SELECT BITS.
```

```
0000            PS0     EQU     0       (PS0) --
                **
                ** EQUATES FOR THE STATUS BYTE, 'STAT'.
                ***
                ***
                **
0007            UD      EQU     7       COUNT DIRECTION?  1 = UP, 0 = DOWN.
0006            MOD_32  EQU     6       IS 'BINCT' MODULO 32?   1 = YES, 0 = NO.
0005            FLASH   EQU     5       BLINK THE DISPLAY?  1 = YES, 0 = NO.
0004            POSCT   EQU     4       DISPLAY POSITION OR COUNT?  1 = POS, 0 = COUNT.
0003            L_SET   EQU     3       VALUE OF 'MODE,PORTD' LAST TIME.
0002            NEGTIV  EQU     2       IS 'BCDCT'NEGATIVE NUMBER?  1 = YES, 0 = NO.
                ***             1       NOT USED.
                ***             0       NOT USED.
                ***
                ***
                ** I/O EQUATES AND DESCRIPTIONS.
                ***
                ***
                ***      PORT A  (I/O)
                ***
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                ***     |          BCD DIGIT #4         |         BCD DIGIT #3          |
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                ***     |  D4   |  C4   |  B4   |  A4   |  D3   |  C3   |  B3   |  A3   |
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                *** BIT     7       6       5       4       3       2       1       0
                ***
                ***
                ***      PORT B  (I/O)
                ***
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                ***     |        DISPLAY CONTROL .      |BCD DIGIT #5 (MOST SIGNIFICANT)|
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                ***     | DECPT | POSTIV|       | BLANK |  D5   |  C5   |  B5   |  A5   |
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                *** BIT     7       6       5       4       3       2       1       0
                ***
0007            DECPT   EQU     7       TO DISPLAY THE DECIMAL POINT...DECPT IS CLEARED
0006            POSTIV  EQU     6       USED TO DISPLAY NEGATIVE SIGN...CLEARED TO SHOW
                ***                     MINUS SIGN.
0004            BLANK   EQU     4       TO BLANK DIGITS 2 AND 3...CLEAR BLANK.
                ***                     DIGITS 4 AND 5 ARE ALWAYS BLANKED.
                ***                     DIGIT 1 IS NEVER BLANKED.
                ***
                ***      PORT C  (I/O)
                ***
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                ***     |          BCD DIGIT #2         |BCD DIGIT #1(LEAST SIGNIFICANT)|
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                ***     |  D2   |  C2   |  B2   |  A2   |  D1   |  C1   |  B1   |  A1   |
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                *** BIT     7       6       5       4       3       2       1       0
                ***
                ***
                ***      PORT D  (INPUT ONLY)
                ***
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                ***     | CH_A  |  INT2 |  CH_B | FUNCT |  SET  |       |       |       |
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                *** BIT     7       6       5       4       3       2       1       0
                ***
0007            CH_A    EQU     7       INDICATES THE STATUS OF CHANNEL A.
0006            INT2    EQU     6       INTERRUPT #2.  USED TO CHANGE DISPLAY MODES.
0005            CH_B    EQU     5       INDICATES THE STATUS OF CHANNEL B.
0004            FUNCT   EQU     4       USED TO PUT THE PROGRAM IN A MODE THAT WILL ALLOW
```

```
                        ***                     'HYST' TO BE INCREMENTED.
          0003          SET     EQU     3       INCREMENTS 'HYST' WHEN TOGGLED AND FUNCT IS LOW.
                        ***
                        ***
                        ********************************************************************************
                        **                                                                              *
                        **                          RAM VARIABLES                                       *
                        **                                                                              *
                        ********************************************************************************
                        **
                        ** RESERVE MEMORY SPACE FOR THE PROGRAM VARIABLES.
                        **
0000                            DATA
                        **
                        **
0000                            ABSOLUTE (ABSOLUTE ADDRESSING USED HERE TO RELATIVE DIRECTIVE)
                        **
0010                            ORG     RAM     START OF RAM.
                        **
                        *** BINARY COUNT.
0010                    BINCT   RMB     3
          0010          HIBIN   EQU     BINCT   HI BYTE.
          0011          MIDBIN  EQU     BINCT+1 MIDDLE BYTE.
          0012          LOBIN   EQU     BINCT+2 LO BYTE.
                        **
                        *** POSITION POINTERS.
0013                    PTR     RMB     4       EACH BYTE POINTS TO A POSITION IN THE
                        **                      TABLE THAT CONTAINS ONE OR TWO DIGITS
                        **                      OF THE BCD POSITION.
          0013          PTR4    EQU       PTR   MOST SIGNIFICANT DIGITS.
          0014          PTR3    EQU       PTR+1
          0015          PTR2    EQU       PTR+2
          0016          PTR1    EQU       PTR+3 LEAST SIGNIFICANT DIGIT.
                        **
                        *** COUNT POINTERS.
0017                    CTPTR   RMB     3       EACH BYTE POINTS TO A POSITION IN THE
                        **                      TABLE THAT CONTAINS TWO OF THE DIGITS
                        **                      IN THE BCD COUNT.
          0017          CTPTR3  EQU     CTPTR   MOST SIGNIFICANT DIGITS.
          0018          CTPTR2  EQU     CTPTR+1
          0019          CTPTR1  EQU     CTPTR+2 LEAST SIGNIFICANT DIGITS.
                        **
                        *** BCD POSITION IN DEGREES.
001A                    DEGRES  RMB     4
          001A          HUNDEG  EQU     DEGRES        CONTENTS X 100.000
          001B          ONEDEG  EQU     DEGRES+1      CONTENTS X   1.000
          001C          HUNDTH  EQU     DEGRES+2      CONTENTS X   0.010
          001D          THOUTH  EQU     DEGRES+3    + CONTENTS X   0.001
                        ***                           --------------------
                        ***                             POSITION IN DEGREES
                        **
                        *** BCD COUNT.
001E                    BCDCT   RMB     3
          001E          TENTHO  EQU     BCDCT         CONTENTS X 10,000
          001F          HUNDRD  EQU     BCDCT+1       CONTENTS X    100
          0020          TENONE  EQU     BCDCT+2     + CONTENTS X      1
                        ***                           ----------------------
                        ***                           NUMBER OF PULSES COUNTED
                        ***
                        *** HYSTERESIS COUNTER. POINTS TO A NUMBER IN THE TABLE THAT IS THE
                        ***      AMOUNT OF HYSTERESIS PRESENT IN THE SYSTEM.  INITIALIZED TO 7.
0021                    HYSTPT  RMB      1
                        **
                        *** POSITION INCREMENT.  CONTAINS A NUMBER, THAT WHEN MULTIPLIED BY 0.001
                        ***      IS THE NUMBER OF DEGREES THAT THE POSITION COUNTER (BCDPOS) IS
                        ***      TO BE INCREMENTED OR DECREMENTED DURING PROGRAM EXECUTION.
```

```
194                     ***     THE VALUE OF 'POSINC', DETERMINED EXPERIMENTALLY, SHOULD BE
195                     ***     7.0312.  SINCE THE PROGRAM IS DESIGNED WORK WITH INTEGERS ONLY
196                     ***     THIS NUMBER IS ROUNDED TO 7.  TO REDUCE THE CUMULATIVE EFFECT OF
197                     ***     THE ROUND OFF, EVERY 32 COUNTS 'POSINC' IS SET EQUAL TO 8.  THIS
198                     ***     AGAIN LEADS TO SOME CUMULATIVE ERROR THAT IS ACCOUNTED FOR BY
199                     ***     SETTING 'POSINC' TO 7 INSTEAD OF 8 WHEN THE COUNT REACHES A
200                     ***     VALUE OF 16384 (2^14).
201                     ***
202  0022               POSINC  RMB     1
203                     ***
204                     *** HYSTERESIS VARIABLES.  USED TO ELIMINATE THE EFFECTS OF BACKLASH ON
205                     ***     THE POSITION MEASUREMENTS.
206                     ***
207  0023               HYST    RMB     1       THE THRESHHOLD VALUE DETERMINED
208                     ***                     EXPERIMENTALLY.
209  0024               HYSTCT  RMB     1       CURRENT AMOUNT OF HYSTERESIS MEASURED.
210                     ***
211                     *** STATUS BYTE.  USED TO KEEP TRACK OF WHAT IS GOING ON.
212                     ***
213  0025               STAT    RMB     1       CURRENT STATUS.
214  0026               LSTAT   RMB     1       PREVIOUS/LAST STATUS.  USED TO KEEP TRACK OF
215                     ***                     L_SET ONLY.
216                     ***
217                     *** TIMER COUNTER.  USED IN CONJUNCTION WITH THE TIMER PRESCALER AND THE
218                     ***     TDR TO KEEP TRACK OF ONE SEC. INTERVALS.  USED IN BLINKING THE
219                     ***     DISPLAY.  INITIALLY SET TO 31, WHEN THE 'FLASH' BIT OF 'STAT'
220                     ***     IS SET.  TIMCT IS DECREMENTED EACH CLOCK INTERRUPT (APPROX. 31
221                     ***     TIMES PER SEC).  RESET TO 31 WHEN CONTENTS GO TO ZERO.
222                     ***     WHEN (TIMCT)=0 THE DISPLAY WILL TOGGLE.
223                     ***
224  0027               TIMCT   RMB     1
225                     **
226                             ENDS
227                     **                              .
228                     ***
229                     ********************************************************************************
230                     **                                                                              *
231                     **                          PAGE ZERO ROM
232                     **                                                                              *
233                     ********************************************************************************
234                     **
235                     **                      INITIALIZATION ROUTINE.
236                     **
237                     **
238  0000                       CODE
239                     **
240  0080                       ORG     ZROM    PAGE ZERO ROM.
241                     **
242  0080                       RELATIVE        RELATIVE ADDRESSING MUST BE USED FOR THE BRANCH.
243                     **
244       0080         RESTRT  EQU     $       THIS IS THE ENTRY POINT WHEN THE RESET
245                     ***                     SWITCH IS PUSHED.
246                     **
247                     ********************************************************************************
248                     **
249                     ***             INITIALIZE THE PC AND CLEAR RAM.
250                     ***
251                     ***
252  0080  9B                  SEI             SET INTERUPT TO AVOID INTERUPTION AND
253  0081  9C                  RSP             RESET THE STACK POINTER. JUST IN CASE!
254                     ***
255  0082  AE 10                LDX     #BINCT  CLEAR ALL OF THE VARIABLES BETWEEN
256  0084  7F           CLRIT   CLR     ,X      'BINCT' AND 'TIMCT' (INCLUSIVE).NOTE
257  0085  5C                  INCX            THAT THIS SETS THE COUNTER AND THE POS-
258  0086  A3 27                CPX     #TIMCT  ITION TO ZERO. THIS MEANS THAT ROTATION
259  0088  23 FA                BLS     CLRIT   SHOULD START IN AN INCREASING (CW)
```

```
                        ***                     DIRECTION FROM THE MOST CCW POSITION
                        ***                     AFTER A RESET.
                        ***
008A                    ABSOLUTE        BACK TO ABSOLUTE ADDRESSING.
                        ***
                        ********************************************************************************
                        ***
                        ***                             ESTABLISH I/O PORTS.
                        ***
008A  A6 FF             LDA     #-1         PORTS A,B,C ARE CONFIGURED AS
008C  B7 04             STA     PORTA+DDR   ALL OUTPUT. PORT D IS ALL INPUT
008E  B7 05             STA     PORTB+DDR   SO THERE IS NO MASK TO SET.
0090  B7 06             STA     PORTC+DDR
                        ***
                        ***
0092  CD 03 4E          JSR     OUTCT       COUNT IS TO BE DISPLAYED INITIALLY.
                        ***
                        ********************************************************************************
                        ***                     SET UP THE STATUS REGISTER.
                        ***
0095  A6 08             LDA     #%00001000  --
0097  B4 03             AND     PORTD         |--> SET UP 'L_SET' BIT OF 'STAT'.
0099  B7 25             STA     STAT        --
                        ***
009B  1C 25             BSET    MOD_32,STAT  0 IS MODULO 32.
                        **
                        ********************************************************************************
                        ***
                        ***                     INITIALIZE HYSTCT.
                        ***
009D  A6 08             LDA     #08
009F  B7 23             STA     HYST
00A1  B7 21             STA     HYSTPT
                        ***
                        ********************************************************************************
                        **
                        **        SET UP THE TIMER FOR A 4 MHZ CRYSTAL / 4 = 1 MHZ CLOCK.
                        ***
                        ***    NOTE:  THE MASK OPTION REGISTER IS IN ROM.  IT IS SET UP AT
                        ***           THE END OF THE PROGRAM.
                        ***
                        *********************   SET UP THE TCR.  *********************************
                        ***
00A3  A6 47             LDA       #BIT6+BIT2+BIT1+BIT0
                        ***             (TIM)|(PS2)(PS1)(PS0)
                        ***(DISABLE INTERRUPT)|(PRESCALE BY 128)
                        ***
00A5  B7 09             STA     TCR
                        ***
                        ***
                        *** SET UP THE TIMER.
                        ***
00A7  A6 FF             LDA     #255    1 MHZ/(128*255) = 30.6 (APPROX. 31)
00A9  B7 08             STA TIMER
                        ***
                        ***************  INITIALIZE THE TIMER COUNTER.  ***********************
                        ***
00AB  A6 1F             LDA     #31     PROVIDES FOR 1 SEC. BLINK INTERVAL.
00AD  B7 27             STA     TIMCT   FOR 2 SEC. INTERVAL JUST USE TIMECT=62, etc.
                        ***
                        ***
                        ********************************************************************************
                        **
                        **                      SET UP MISCELLANEOUS REGISTER.
                        **
00AF  1D 0A            BCLR    B6,MR    ENABLES THE SECOND INTERRUPT.
```

```
                        **
                        **
00B1  9A                        CLI             CLEAR THE INTERRUPT MASK TO GET STARTED.
                        ***
00B2                            RELATIVE        RELATIVE ADDRESSING MUST BE USED FOR THE
                        ***                     REMAINDER OF THE PROGRAM.
                        ***
                        ********************************************************************************
                        **
                        ** WAIT LOOP.  EXECUTES, UNTIL AN INTERRUPT OCCURS.
                        **
00B2  09 03 0B          PAUSE   BRCLR   FUNCT,PORTD,CHHYST WANT TO CHANGE HYST?
                        **                                  YES...GO TO CHHYST.
00B5  06 03 04                  BRSET   SET,PORTD,SBIT      NO...'SET,PORTD' SET?
00B8  17 25                     BCLR    L_SET,STAT              NO...CLEAR 'L_SET,STAT'
00BA  20 F6                     BRA     PAUSE                   AND LOOP.
00BC  16 25             SBIT    BSET    L_SET,STAT              YES...SET 'L_SET,STAT'
00BE  20 F2                     BRA     PAUSE                   AND...LOOP
                        **
                        ********************************************************************************
                        **
                        ** HYSTERESIS MODIFICATION ROUTINE.  PERMITS MODIFICATION OF THE
                        ** HYSTERESIS BUFFER WITHOUT REPROGRAMMING.
                        **
00C0  A6 40             CHHYST  LDA     #BIT6               DISABLE TIMER INTERRUPT.
00C2  B7 09                     STA     TCR
                        ***
00C4  A6 08                     LDA     #%00001000          SAVE 'L_SET'
00C6  B4 25                     AND     STAT                INTO
00C8  B7 26                     STA     LSTAT               'LSTAT'.
00CA  A6 08                     LDA     #%00001000
00CC  B4 03                     AND     PORTD               'SET,PORTD' --> ACCUMULATOR
00CE  B1 26                     CMP     LSTAT               HAS THE SET SWITCH BEEN CHANGED?
00D0  27 15                     BEQ     DISPLA
                        ***                                 YES...
00D2  A6 08                     LDA     #%00001000          --
00D4  B8 25                     EOR     STAT                  |-->CHANGE 'L_SET,STAT',
00D6  B7 25                     STA     STAT                --
00D8  3C 23                     INC     HYST                THEN INCREMENT THE HYSTERESIS
00DA  3C 21                     INC     HYSTPT              POINTER AND 'HYST'...
                        ***
00DC  B6 21                     LDA     HYSTPT            --
00DE  A1 19                     CMP     #25                 --
00E0  23 05                     BLS     DISPLA                --
                        ***                                     -- BUT NOT ABOVE 25.
00E2  4F                        CLRA                          --       THEN--->|
00E3  B7 23                     STA     HYST                --                 |
00E5  B7 21                     STA     HYSTPT            --                   |
                        ***                                                    |
00E7  A6 00             DISPLA  LDA     #%00000000          NO... JUST--------->|
00E9  B7 00                     STA     PORTA             --                   |
00EB  A6 C0                     LDA     #%11000000          --                 |
00ED  B7 01                     STA     PORTB                 --             \|/
                        ***                                       -- DISPLAY CURRENT 'HYST'.
00EF  BE 21                     LDX     HYSTPT                --
00F1  D6 03 BE                  LDA     TABLE,X               --
00F4  B7 02                     STA     PORTC             --
                        ***                                 IS 'HYST' SETTING COMPLETE?
00F6  09 03 C7                  BRCLR   FUNCT,PORTD,CHHYST NO... KEEP CHECKING 'SET'.
00F9  08 25 05                  BRSET   POSCT,STAT,SHOPOS  YES... RESET THE DISPLAY.
00FC  CD 03 4E                  JSR     OUTCT
00FF  20 03                     BRA     DUNCHG
                        ***
0101  CD 03 68          SHOPOS  JSR     OUTPOS
                        ***
0104  0B 25 04          DUNCHG  BRCLR   FLASH,STAT,NO_INT   IF THE DISPLAY IS TO BLINK...
```

```
392  0107  A6 07          LDA   #BIT2+BIT1+BIT0   ENABLE TIMER INTERRUPT AND RESET
393  0109  B7 09          STA   TCR              TIMER PRESCALER
394  010B  20 A5    NO_INT BRA   PAUSE           PRIOR TO RETURNING.
395                  ***
396                  **
397                  ********************************************************************************
398                  ** MAXIMUM EXECUTION TIME FOR THE REMAINDER OF THE PROGRAM OCCURS
399                  ** IF THE COUNTER ROTATES THROUGH ZERO AS THE DISPLAY MODE IS CHANGED
400                  ** FROM THE BLINKING MODE TO THE COUNT MODE AT THE SAME TIME THAT THE
401                  ** BLINKING ROUTINE IS CAUSING THE DISPLAY TO TOGGLE TO SHOW THE
402                  ** POSITION IN DEGREES.
403                  **     MAXIMUM EXECUTION TIME = 140 + 184 + 708 = 1032 CLOCK CYCLES.
404                  ********************************************************************************
405                  **
406                  ** MODE CHANGE ROUTINE.  CHANGES THE DISPLAY MODE FROM
407                  **       COUNT -> POSITION -> BLINKING -> COUNT ->....(ETC.)
408                  **       MAXIMUM EXECUTION TIME OF 181 CLOCK CYCLES OCCURS WHEN THE
409                  **       DISPLAY MODE IS CHANGED FROM DISPLAYING THE COUNT TO DISPLAYING
410                  **       THE POSITION (IN DEGREES).
411                  **       IF THE DISPLAY IS CHANGED FROM BLINKING TO A COUNT DISPLAY
412                  **       EXECUTION TIME IS 140 CLOCK CYCLES.
413                  **
414  010D  1F 0A    CHMODE BCLR  B7,MR             AVOID REPEATED INTERRUPTS.
415                  **
416  010F  0A 25 10         BRSET  FLASH,STAT,DIS_CT  IF FLASHING, DISPLAY COUNT...
417  0112  09 25 07         BRCLR  POSCT,STAT,DISPOS  IF SHOWING COUNT, DISPLAY POSITION...
418  0115  1A 25            BSET   FLASH,STAT         ELSE, BLINK.
419                  **
420  0117  A6 07            LDA    #BIT2+BIT1+BIT0    ENABLE TIMER INTERRUPT AND RESET
421  0119  B7 09            STA    TCR                TIMER PRESCALER.
422  011B  80              RTI
423                  **
424  011C  18 25    DISPOS  BSET   POSCT,STAT      --
425  011E  CD 03 68         JSR    OUTPOS            |-- DISPLAY CURRENT POSITION, AND WAIT.
426  0121  80               RTI                    --
427                  **
428  0122  A6 47    DIS_CT  LDA    #BIT6+BIT2+BIT1+BIT0  DISABLE TIMER INTERRUPT AND RESET
429  0124  B7 09            STA    TCR                   TIMER PRESCALER.
430  0126  19 25            BCLR   POSCT,STAT      --
431  0128  1B 25            BCLR   FLASH,STAT       |
432                  **                             |-- DISPLAY CURRENT COUNT, AND WAIT.
433  012A  CD 03 4E         JSR    OUTCT            |
434  012D  80               RTI                    --
435                  **
436                  ********************************************************************************
437                  **
438                  ** BLINK ROUTINE.  INTERRUPT ROUTINE TO CHANGE THE DISPLAY FROM POSITION
439                  **       TO COUNT OR VICE VERSA EVERY 31 ST TIMER INTERRUPT IF THE
440                  **       'FLASH' BIT OF 'STAT' IS SET.
441                  **       MAXIMUM EXECUTION TIME OF 184 CLOCK CYCLES OCCURS WHEN THE
442                  **       DISPLAY IS TOGGLED FROM A COUNT DISPLAY TO A POSITION DISPLAY.
443                  **
444       012E       BLINK  EQU    $
445  012E  0F 09 DC         BRCLR  TIR,TCR,CHMODE       IF THE INTERRUPT WAS NOT A TIMER
446                  **                                 INTERRUPT IT MUST BE FROM INT2.
447                  **
448  0131  1F 09            BCLR   TIR,TCR              AVOID REPEATED TIMER INTERRUPTS.
449                  **
450  0133  3A 27            DEC    TIMCT                IF THERE HAVE BEEN 31 TIMER
451  0135  27 01            BEQ    CHGDIS               INTERRUPTS  (1 SEC), IT'S TIME TO
452                  **                                 CHANGE THE DISPLAY.
453  0137  80               RTI                         OTHERWISE, IT'S BACK TO WORK.
454                  **
455  0138  A6 1F    CHGDIS  LDA    #31                  RESET TIMCT TO 31 (1 SEC. INTERVAL).
456  013A  B7 27            STA    TIMCT
457                  **
```

```
458  013C  B6 25              LDA     STAT            --
459  013E  A8 10              EOR     #%00010000        |-- CHANGE 'POSCT' BIT OF 'STAT'.
460  0140  B7 25              STA     STAT            --
461                       **
462  0142  08 25 04           BRSET   POSCT,STAT,POSOUT     DECIDE ON CORRECT DISPLAY.
463                       **
464                       ************ CHANGE THE DISPLAY TO SHOW THE COUNT.....  ***************
465                       **
466  0145  CD 03 4E           JSR     OUTCT
467  0148  80                 RTI
468                       **
469                       ************ OR HAVE THE DISPLAY SHOW THE POSITION.  ******************
470                       **
471  0149  CD 03 68       POSOUT  JSR     OUTPOS
472  014C  80                 RTI
473                       **
474                       ********************************************************************************
475                       **
476                       **                          COUNT ROUTINE.
477                       **        WHEN A COUNT IS RECEIVED THIS IS THE ENTRY POINT .
478                       **        MAXIMUM EXECUTION TIME OF 708 CLOCK CYCLES OCCURS WHEN THE
479                       **        COUNTER ROTATES CCW THROUGH ZERO AND THE POSITION (IN DEGREES)
480                       **        IS BEING DISPLAYED.
481                       **
482                       **
483                       ** CURRENT DIRECTION OF ROTATION IS DETERMINED BY INSPECTING THE STATUS
484                       ** OF 'CH_A' AND 'CH_B'.  THE FOUR POSSIBILITIES AND THE ASSOCIATED
485                       ** DIRECTION OF ROTATION ARE AS SHOWN BELOW.  NOTE THAT THIS SCHEME
486                       ** PREVENTS MULTIPLE OSCILLATIONS ABOUT A SINGLE POINT FROM
487                       ** REPEATEDLY INCREMENTING OR DECREMENTING THE COUNTER.
488                       **
489                       **   +--------+---------+-----------------+------------------+
490                       **   |  CH_A  |   CH_B  |   DIRECTION     |  COUNT THE PULSE? |
491                       **   |        |         |  OF ROTATION    |                   |
492                       **   +--------+---------+-----------------+------------------+
493                       **   |   LO   |    LO   |      CW         |        NO         |
494                       **   |   LO   |    HI   |      CCW        |        YES        |
495                       **   |   HI   |    LO   |      CCW        |        NO         |
496                       **   |   HI   |    HI   |      CW         |        YES        |
497                       **   +--------+---------+-----------------+------------------+
498                       **
499                       ********  FIRST SEE IF WE ARE SUPPOSED TO COUNT THIS INTERUPT.  ********
500                       **
501       014D            COUNT   EQU     $
502  014D  0A 03 01           BRSET   CH_B,PORTD,OKCT    IF CH_B IS LO WE DON'T COUNT THE
503  0150  80                 RTI                        INTERRUPT.
504                       **
505                       ************** IF THE INTERRUPT IS VALID UPDATE 'STAT'.  **************
506                       **
507  0151  A6 7F           OKCT    LDA     #%01111111
508  0153  B4 25              AND     STAT            SAVE ALL OF THE OLD 'STAT' EXCEPT THE
509  0155  B7 25              STA     STAT            DIRECTION OF ROTATION.
510  0157  A6 80              LDA     #%10000000
511  0159  B4 03              AND     PORTD           'CH_A,PORTD' INDICATES THE DIRECTION
512                       *                          OF ROTATION AND BECOMES 'UD,STAT'.
513  015B  BA 25              ORA     STAT            ADD THE RESULTS TO GET
514  015D  B7 25              STA     STAT            THE NEW 'STAT'.
515                       **
516                       ** DECIDE IF THE "SLACK" DUE TO BACKLASH/HYSTERESIS HAS BEEN TAKEN OUT.
517                       **
518  015F  0E 25 09           BRSET   UD,STAT,HYSTCK  IF ROTATING CW SEE BELOW.
519  0162  B6 24              LDA     HYSTCT          ELSE, SEE IF WE DECREMENT THIS TIME.
520  0164  27 60              BEQ     CCW             IF HYSTCT=0, GO TO THE COUNT DOWN
521                       **                          ROUTINE.
522  0166  A0 01              SUB     #1              ELSE, DECREMENT THE HYSTERESIS COUNTER,
523  0168  B7 24              STA     HYSTCT
```

```
524  016A  80              RTI                 AND WAIT FOR THE NEXT INTERRUPT.
525                    **
526  016B  B6 23       HYSTCK LDA    HYST       IF ROTATING CW....
527  016D  B1 24              CMP    HYSTCT     AND  HYST = HYSTCT ....
528  016F  27 03              BEQ    CW         COUNT THE PULSE .
529  0171  3C 24              INC    HYSTCT     ELSE, INCREMENT THE HYSTERESIS COUNTER,
530  0173  80                 RTI               AND WAIT FOR ANOTHER PULSE.
531                    **
532                    **
533                    ********************************************************************************
534                    **
535                    **                        CLOCKWISE ROUTINE.
536                    **
537       0174         CW     EQU    $
538                    **
539                    ***
540                    **************  INCREMENT THE BINARY COUNTER (BINCT).  *****************
541                    ***
542  0174  B6 12              LDA    LOBIN   BEGIN AT THE LSB OF THE BINARY COUNTER.
543  0176  AB 01              ADD    #1      LOBIN = LOBIN + 1 ; CARRY -> C,CCR
544  0178  B7 12              STA    LOBIN
545                    ***
546  017A  B6 11              LDA    MIDBIN
547  017C  A9 00              ADC    #0              ADD THE CARRY TO THE MIDDLE BYTE.
548  017E  B7 11              STA    MIDBIN
549                    ***
550  0180  B6 10              LDA    HIBIN
551  0182  A9 00              ADC    #0              ADD THE CARRY TO THE HIGH BYTE.
552  0184  B7 10              STA    HIBIN
553                    ***
554                    ***
555                    ******************  CLR/SET MOD_32 APPROPRIATELY.  **********************
556                    ***
557                    ***     THE FOLLOWING SEVERAL LINES OF CODE ARE PRETTY MESSY.  ALL THAT
558                    ***     IS BEING DONE IS TO ENSURE THAT THE SCALE FACTOR IS SET PROPERLY.
559                    ***     FOR THE PAN AXIS THE SCALE FACTOR IS;
560                    ***
561                    ***                     1 PULSE => 0.007097 DEGREES
562                    ***
563  0186  B6 12              LDA    LOBIN        IF THE LOW FIVE BITS OF 'LOBIN' ARE NOT
564  0188  A4 1F              AND    #%00011111   ZERO THEN THE NUMBER ISN'T A MODULO 32 NUMBER.
565  018A  26 0F              BNE    NOT_32
566  018C  B6 11              LDA    MIDBIN       IF THE LOW SIX BITS OF 'MIDBIN' ARE ZERO
567  018E  27 07              BEQ    MOD          AND 'HIBIN' .NE. ZERO
568  0190  A4 3F              AND    #%00111111   THEN THE NUMBER IS MODULO 16,384, AND WE
569  0192  26 03              BNE    MOD          DON'T WANT TO SET 'MOD_32,STAT', UNLESS
570  0194  0D 11 04           BRCLR  B6,MIDBIN,NOT_32  THE NUMBER IS ALSO MODULO 32,768.
571                    ***
572  0197  1C 25       MOD    BSET   MOD_32,STAT
573  0199  20 02              BRA    DIRCHK
574                    ***
575  019B  1D 25       NOT_32 BCLR   MOD_32,STAT
576                    ***
577                    ***
578  019D  B6 10       DIRCHK LDA    HIBIN
579  019F  2B 1D              BMI    CWNEG        IF HIBIN < 0 , WE'RE ROTATING CCW TOWARD
580                    ***                        THE ORIGIN.
581                    ***
582  01A1  26 14              BNE    CWPOS
583  01A3  B6 11              LDA    MIDBIN       ELSE IF BINCT .NE. 0
584  01A5  26 10              BNE    CWPOS        WE'RE ROTATING CW
585  01A7  B6 12              LDA    LOBIN        AWAY FROM THE ORIGIN.
586  01A9  26 0C              BNE    CWPOS
587
588                    ***                        ELSE, WE'VE ROTATED CW THROUGH THE ORIGIN.
589  01AB  15 25              BCLR   NEGTIV,STAT  CLR NEGATIVE SIGN.
```

```
01AD  AE 13           LDX   #PTR4   --
01AF  7F              CLRIT2 CLR   ,X       --
01B0  5C              INCX                  --RESET ALL COUNTERS AND DEGRES TO ZERO.
01B1  A3 1D           CPX   #THOUTH  --
01B3  23 FA           BLS   CLRIT2  --
01B5  20 68           BRA   UPOUT         UPDATE OUTPUT.
                      ***
01B7  AD 74           CWPOS  BSR   ADDBCD
01B9  CD 02 6A        JSR   INCPOS
01BC  20 64           BRA   UPOUT
                      ***
01BE  CD 02 CA        CWNEG  JSR   SUBBCD
01C1  CD 02 6A        JSR   INCPOS
01C4  20 5C           BRA   UPOUT
                      ***
                      **
                      ********************************************************************************
                      **
                      **                    COUNTER-CLOCKWISE ROUTINE.
                      **
      01C6            CCW   EQU   $
                      **
                      ***
                      ******************  CLR/SET MOD_32 APPROPRIATELY.  **********************
                      ***
                      ***     AGAIN SET THE SCALE FACTOR TO;
                      ***
                      ***                      1 PULSE => 0.007097 DEGREES
                      ***
01C6  B6 12           LDA   LOBIN         IF THE LOW FIVE BITS OF 'LOBIN' ARE NOT
01C8  A4 1F           AND   #%00011111    ZERO THEN THE NUMBER ISN'T A MODULO 32 NUMBER.
01CA  26 0F           BNE   NO_32
01CC  B6 11           LDA   MIDBIN        IF THE LOW SIX BITS OF 'MIDBIN' ARE ZERO
01CE  27 07           BEQ   MODLO         AND 'HIBIN' .NE. ZERO
01D0  A4 3F           AND   #%00111111    THEN THE NUMBER IS MODULO 16,384, AND WE
01D2  26 03           BNE   MODLO         DON'T WANT TO SET 'MOD_32,STAT', UNLESS
01D4  0D 11 04        BRCLR B6,MIDBIN,NO_32  THE NUMBER IS ALSO MODULO 32,768.
                      ***
01D7  1C 25           MODLO  BSET   MOD_32,STAT
01D9  20 02           BRA   DECBIN
                      ***
01DB  1D 25           NO_32  BCLR   MOD_32,STAT
                      ***
                      ***
                      ***************  DECREMENT THE BINARY COUNTER (BINCT).  ***************
                      ***
01DD  B6 12           DECBIN LDA    LOBIN   BEGIN AT THE LSB OF THE BINARY COUNTER.
01DF  A0 01           SUB   #1      LOBIN = LOBIN - 1 ; BORROW -> C,CCR
01E1  B7 12           STA   LOBIN
                      ***
01E3  B6 11           LDA   MIDBIN
01E5  A2 00           SBC   #0      SUBTRACT THE CARRY FROM THE MIDDLE BYTE.
01E7  B7 11           STA   MIDBIN
                      ***
01E9  B6 10           LDA   HIBIN
01EB  A2 00           SBC   #0      SUBTRACT THE CARRY FROM THE HIGH BYTE.
01ED  B7 10           STA   HIBIN
                      ***
01EF  B6 10           LDA   HIBIN
01F1  2A 29           BPL   CCWPOS        IF HIBIN .GE. 0 , WE'RE ROTATING CCW TOWARD
                      ***                 THE ORIGIN.
01F3  A6 FF           LDA   #-1     --
01F5  B1 10           CMP   HIBIN    --
01F7  26 1C           BNE   CCWNEG     --  ELSE IF BINCT .NE. -1 ,
01F9  B1 11           CMP   MIDBIN      -- WE'RE ROTATING CCW AWAY
01FB  26 18           BNE   CCWNEG     --  FROM THE ORIGIN.
```

```
656  01FD  B1 12          CMP    LOBIN    --
657  01FF  26 14          BNE    CCWNEG   --
658                  ***
659  0201  14 25          BSET   NEGTIV,STAT   ELSE, WE'VE GONE THROUGH ORIGIN IN CCW
660                  ***                        DIRECTION.  SET NEGATIVE SIGN.
661                  ***                        AND SET ALL COUNTERS APPROPRIATELY.
662  0203  A6 03          LDA    #03      --
663  0205  B7 13          STA    PTR4       --
664  0207  B7 1A          STA    HUNDEG       -- DEGRES = 360.00
665  0209  A6 3C          LDA    #60        --
666  020B  B7 14          STA    PTR3     --
667  020D  AE 15          LDX    #PTR2    --
668  020F  7F             CLR    ,X         --
669  0210  5C             INCX                -- EVERYTHING ELSE IS ZERO BEFORE CHANGE.
670  0211  A3 19          CPX    #CTPTR1    --
671  0213  23 FA          BLS    CLREM    --
672                  ***
673  0215  AD 16          BSR    ADDBCD
674  0217  CD 02 FD       JSR    DECPOS
675  021A  20 06          BRA    UPOUT
676                  ***
677  021C  CD 02 CA       JSR    SUBBCD
678  021F  CD 02 FD       JSR    DECPOS
679                  ***
680                  ***
681                  **
682                  ********************************************************************************
683                  **
684                  ** OUTPUT ROUTINE. ROUTINE TO PRINT DATA TO THE OUTPUT PORTS.  BY
685                  **       CALLING THE APPROPRIATE SUBROUTINE.('OUTCT' TO OUTPUT THE
686                  **       THE COUNT AND 'OUTPOS' TO OUTPUT THE POSITION).
687                  **
688       0222       UPOUT  EQU    $
689                  **
690  0222  09 25 04          BRCLR  POSCT,STAT,PUTCT
691                  **
692  0225  CD 03 68          JSR    OUTPOS
693  0228  80                RTI
694                  **
695  0229  CD 03 4E       PUTCT  JSR    OUTCT
696  022C  80                RTI
697                  **
698                  ********************************************************************************
699                  **********  SUBROUTINE TO INCREMENT THE BCD COUNTER (BCDCT).  *********
700                  ***
701  022D  B6 19          ADDBCD LDA    CTPTR1
702  022F  AB 01                 ADD    #1
703  0231  A1 63                 CMP    #99      CTPTR > 99 ?
704  0233  23 05                 BLS    OK1      NO, WE'RE OK HERE. LOOK UP THE FIRST TWO DIGITS.
705  0235  A0 64                 SUB    #100     YES... MODIFY THE CTPTR,
706  0237  99                   SEC             SET THE CARRY, AND
707  0238  20 01                 BRA    OK1A     USE TABLE LOOK UP.
708                  ***
709  023A  98             OK1    CLC                    NO CARRY EXISTS IF WE ENTER AT THIS POINT.
710  023B  B7 19          OK1A   STA    CTPTR1   --
711  023D  97                    TAX                --
712                  ***                              -- LOOK UP THE TWO LEAST SIGNIFICANT DIGITS.
713  023E  D6 03 BE              LDA    TABLE,X    --
714  0241  B7 20                 STA    TENONE   --
715  0243  24 24                 BCC    NOMO             AND CONTINUE ONLY IF THERE WAS A CARRY.
716                  ***
717                  ***
718  0245  B6 18                 LDA    CTPTR2
719  0247  A9 00                 ADC    #0       ADD THE CARRY.
720  0249  A1 63                 CMP    #99      CTPTR > 99 ?
721  024B  23 05                 BLS    OK2      NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
```

```
722  024D  A0 64              SUB   #100   YES... MODIFY THE CTPTR,
723  024F  99                 SEC          SET THE CARRY, AND
724  0250  20 01              BRA   OK2A   USE TABLE LOOK UP.
725                    ***
726  0252  98           OK2    CLC                 NO CARRY EXISTS IF WE ENTER AT THIS POINT.
727  0253  B7 18        OK2A   STA   CTPTR2 --
728  0255  97                 TAX            --
729                    ***                      -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
730  0256  D6 03 BE            LDA   TABLE,X  --
731  0259  B7 1F              STA   HUNDRD --
732  025B  24 0C              BCC   NOMO           AND CONTINUE ONLY IF THERE WAS A CARRY.
733                    ***
734  025D  B6 17              LDA   CTPTR3
735  025F  A9 00              ADC   #0             ADD THE CARRY.
736  0261  B7 17              STA   CTPTR3 --
737  0263  97                 TAX            --
738                    ***                      -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
739  0264  D6 03 BE            LDA   TABLE,X  --
740  0267  B7 1E              STA   TENTHO --
741                    ***
742  0269  81           NOMO   RTS
743                    ***
744                    ********************************************************************************
745                    *******  SUBROUTINE TO INCREMENT THE POSITION COUNTER (DEGRES).  *******
746                    ***
747                    ****  FIRST CHECK TO SEE IF THE BINARY COUNTER HAS REACHED A MODULO 32
748                    ****    NUMBER.
749                    ****
750  026A  0D 25 04    INCPOS BRCLR  MOD_32,STAT,INC7   'MOD_32,STAT' SET ?
751                    ****
752  026D  A6 08              LDA   #8                  YES ...
753  026F  20 02              BRA   INC           INCREMENT THE POSITION BY 0.008 DEGREES.
754                    ****
755  0271  A6 07        INC7   LDA   #7                  NO ....
756  0273  B7 22        INC    STA   POSINC         INCREMENT THE POSITION BY 0.007 DEGREES.
757                    ****
758                    **** ROUTINE TO INCREMENT THE POSITION COUNTER ,'DEGREES',BY A
759                    ****    PREDETERMINED AMOUNT, 'POSINC'.
760                    ****
761  0275  B6 16              LDA   PTR1
762  0277  BB 22              ADD   POSINC
763  0279  A1 09              CMP   #9       PTR1 > 9 ?
764  027B  23 05              BLS   OK3      NO, WE'RE OK HERE.  LOOK UP THE FIRST DIGIT.
765  027D  A0 0A              SUB   #10      YES... MODIFY THE CTPTR,
766  027F  99                 SEC            SET THE CARRY, AND
767  0280  20 01              BRA   OK3A     USE TABLE LOOK UP.
768                    ****
769  0282  98           OK3    CLC                   NO CARRY EXISTS IF WE ENTER AT THIS POINT.
770  0283  B7 16        OK3A   STA   PTR1   --
771  0285  97                 TAX              --
772                    ****                       -- LOOK UP THE LEAST SIGNIFICANT DIGIT.
773  0286  D6 03 BE            LDA   TABLE,X  --
774  0289  B7 1D              STA   THOUTH --
775  028B  24 3C              BCC   DONE            AND CONTINUE ONLY IF THERE WAS A CARRY.
776                    ****
777                    ****
778  028D  B6 15              LDA   PTR2
779  028F  A9 00              ADC   #0       ADD THE CARRY.
780  0291  A1 63              CMP   #99      PTR2 > 99 ?
781  0293  23 05              BLS   OK4      NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
782  0295  A0 64              SUB   #100     YES...MODIFY THE CTPTR,
783  0297  99                 SEC            SET THE CARRY,
784  0298  20 01              BRA   OK4A     AND USE TABLE LOOK UP.
785                    ****
786  029A  98           OK4    CLC                   NO CARRY EXISTS IF WE ENTER AT THIS POINT.
787  029B  B7 15        OK4A   STA   PTR2   --
```

```
788  029D  97              TAX             --
789                  ****                    -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
790  029E  D6 03 BE       LDA   TABLE,X   --
791  02A1  B7 1C          STA   HUNDTH  --
792  02A3  24 24          BCC   DONE          AND CONTINUE ONLY IF THERE WAS A CARRY.
793                  ****
794                  ****
795  02A5  B6 14          LDA   PTR3
796  02A7  A9 00          ADC   #0      ADD THE CARRY.
797  02A9  A1 63          CMP   #99     PTR3 > 99 ?
798  02AB  23 05          BLS   OK5     NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
799  02AD  A0 64          SUB   #100    YES... MODIFY THE CTPTR,
800  02AF  99             SEC           SET THE CARRY, AND
801  02B0  20 01          BRA   OK5A    USE TABLE LOOK UP.
802                  ****
803  02B2  98             OK5   CLC                 NO CARRY EXISTS IF WE ENTER AT THIS POINT.
804  02B3  B7 14          OK5A  STA   PTR3    --
805  02B5  97             TAX             --
806                  ****                    -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
807  02B6  D6 03 BE       LDA   TABLE,X   --
808  02B9  B7 1B          STA   ONEDEG  --
809  02BB  24 0C          BCC   DONE          AND CONTINUE ONLY IF THERE WAS A CARRY.
810                  ****
811  02BD  B6 13          LDA   PTR4
812  02BF  A9 00          ADC   #0      ADD THE CARRY.
813  02C1  B7 13          STA   PTR4    --
814  02C3  97             TAX             --
815                  ****                    -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
816  02C4  D6 03 BE       LDA   TABLE,X   --
817  02C7  B7 1A          STA   HUNDEG  --
818                  ****
819  02C9  81             DONE  RTS
820                  ***
821                  **
822                  ********************************************************************************
823                  ********  SUBROUTINE TO DECREMENT THE BCD COUNTER (BCDCT).  ************
824                  ***
825  02CA  B6 19          SUBBCD LDA    CTPTR1
826  02CC  A0 01          SUB   #1      CTPTR > 99 ?
827  02CE  24 03          BCC   OK6     NO, WE'RE OK HERE. LOOK UP THE FIRST TWO DIGITS.
828  02D0  AB 64          ADD   #100    YES, MODIFY THE CTPTR, AND
829  02D2  99             SEC           GENERATE A BORROW.
830                  ***
831  02D3  B7 19          OK6   STA   CTPTR1  --
832  02D5  97             TAX             --
833                  ***                     -- LOOK UP THE TWO LEAST SIGNIFICANT DIGITS.
834  02D6  D6 03 BE       LDA   TABLE,X   --
835  02D9  B7 20          STA   TENONE  --
836  02DB  24 1F          BCC   COMPLT        AND CONTINUE ONLY IF THERE WAS A BORROW.
837                  ***
838                  ***
839  02DD  B6 18          LDA   CTPTR2
840  02DF  A2 00          SBC   #0      SUBTRACT THE CARRY. CTPTR > 99 ?
841  02E1  24 03          BCC   OK7     NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
842  02E3  AB 64          ADD   #100    YES, MODIFY THE CTPTR, AND
843  02E5  99             SEC           GENERATE A BORROW.
844                  ***
845  02E6  B7 18          OK7   STA   CTPTR2  --
846  02E8  97             TAX             --
847                  ***                     -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
848  02E9  D6 03 BE       LDA   TABLE,X   --
849  02EC  B7 1F          STA   HUNDRD  --
850  02EE  24 0C          BCC   COMPLT          AND CONTINUE ONLY IF THERE WAS A CARRY.
851                  ***
852  02F0  B6 17          LDA   CTPTR3
853  02F2  A2 00          SBC   #0      SUBTRACT THE BORROW.
```

```
02F4  B7 17          STA   CTPTR3  --
02F6  97             TAX           --
                ***                    -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
02F7  D6 03 BE       LDA   TABLE,X  --
02FA  B7 1E          STA   TENTHO  --
                ***
02FC  81        COMPLT RTS
                ***
                ********************************************************************************
                *******  SUBROUTINE TO DECREMENT THE POSITION COUNTER (DEGRES).  *******
                ***
                ****  FIRST CHECK TO SEE IF THE BINARY COUNTER HAS REACHED A MODULO 32
                ****    NUMBER.
                ****
02FD  0D 25 04  DECPOS BRCLR  MOD_32,STAT,DEC7       'MOD_32,STAT' SET ?
                ****
0300  A6 08          LDA   #8                       YES...
0302  20 02          BRA   DEC           DECREMENT THE POSITION BY 0.008 DEGREES.
                ****
0304  A6 07        DEC7  LDA   #7                       NO ....
0306  B7 22        DEC   STA   POSINC        DECREMENT THE POSITION BY 0.007 DEGREES.
                ****
                **** ROUTINE TO DECREMENT THE POSITION COUNTER ,'DEGREES',BY A
                ****    PREDETERMINED AMOUNT, 'POSINC'.
                ****
0308  B6 16          LDA   PTR1
030A  B0 22          SUB   POSINC  PTR1 < 0 ?
030C  24 03          BCC   OK8     NO, WE'RE OK HERE. LOOK UP THE FIRST DIGIT.
030E  AB 0A          ADD   #10     YES, MODIFY THE CTPTR, AND
0310  99             SEC           GENERATE A BORROW.
                ****
0311  B7 16        OK8   STA   PTR1    --
0313  97             TAX             --     .
                ****                      -- LOOK UP THE LEAST SIGNIFICANT DIGIT.
0314  D6 03 BE       LDA   TABLE,X  --
0317  B7 1D          STA   THOUTH  --
0319  24 32          BCC   DUNSUB       AND CONTINUE ONLY IF THERE WAS A BORROW.
                ***
                ***
031B  B6 15          LDA   PTR2
031D  A2 00          SBC   #0      SUBTRACT THE BORROW.  PTR2 < 0 ?
031F  24 03          BCC   OK9     NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
0321  AB 64          ADD   #100    YES, MODIFY THE CTPTR, AND
0323  99             SEC           GENERATE A BORROW.
                ***
0324  B7 15        OK9   STA   PTR2    --
0326  97             TAX             --
                ***                       -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
0327  D6 03 BE       LDA   TABLE,X  --
032A  B7 1C          STA   HUNDTH  --
032C  24 1F          BCC   DUNSUB       AND CONTINUE ONLY IF THERE WAS A CARRY.
                ***
                ***
032E  B6 14          LDA   PTR3
0330  A2 00          SBC   #0      SUBTRACT THE BORROW.  PTR3 < 0 ?
0332  24 03          BCC   OK10    NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
0334  AB 64          ADD   #100    YES, MODIFY THE CTPTR, AND
0336  99             SEC           GENERATE A BORROW.
                ****
0337  B7 14        OK10  STA   PTR3    --
0339  97             TAX             --
                ****                      -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
033A  D6 03 BE       LDA   TABLE,X  --
033D  B7 1B          STA   ONEDEG  --
033F  24 0C          BCC   DUNSUB       AND CONTINUE ONLY IF THERE WAS A CARRY.
                ****
```

```
0341  B6 13              LDA     PTR4
0343  A2 00              SBC     #0      SUBTRACT THE BORROW.
0345  B7 13              STA     PTR4    --
0347  97                TAX               --
                  ****                        -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
0348  D6 03 BE          LDA     TABLE,X   --
034B  B7 1A              STA     HUNDEG  --
                  ****
034D  81          DUNSUB  RTS
                  ***
                  **
                  **
                  ********************************************************************************
                  **
                  ** OUTPUT COUNT (OUTCT).  SUBROUTINE TO MOVE THE CURRENT COUNT (BCDCT)
                  **       TO THE OUTPUT PORTS.  REMOVES THE DECIMAL POINT FROM THE
                  **       DISPLAY AND BLANKS ALL BUT THE LEAST SIGNIFICANT DIGIT. ALSO
                  **       SETS THE MINUS SIGN IF APPROPRIATE.
                  **
034E      OUTCT   EQU     $
                  **
034E  B6 20              LDA     TENONE
0350  B7 02              STA     PORTC
                  **
0352  B6 1F              LDA     HUNDRD
0354  B7 00              STA     PORTA
                  **
0356  B6 1E              LDA     TENTHO
0358  B7 01              STA     PORTB
                  **
035A  1E 01              BSET    DECPT,PORTB
035C  19 01              BCLR    BLANK,PORTB
                  **
035E  04 25 04           BRSET   NEGTIV,STAT,MINUS
0361  1C 01              BSET    POSTIV,PORTB
0363  20 02              BRA     ALLDUN
                  **
0365  1D 01       MINUS  BCLR    POSTIV,PORTB
                  **
0367  81          ALLDUN  RTS
                  **
                  **
                  ** OUTPUT POSITION (OUTPOS).  SUBROUTINE TO MOVE THE CURRENT POSITION
                  **       COUNT (BCDCT) TO THE OUTPUT PORTS.  THE DECIMAL POINT IS
                  **       DISPLAYED , AND ONLY THE MOST SIGNIFICANT DIGIT IS BLANKED.
                  **
0368      OUTPOS  EQU     $
                  **
0368  B6 1D              LDA     THOUTH  --
036A  A1 05              CMP     #5        --
036C  25 38              BLO     TRUNC       --    IF 5 > 'THOUTH' SIMPLY TRUNCATE THE
036E  B6 1C              LDA     HUNDTH        -- DISPLAY.  OTHERWISE...
0370  A4 09              AND     #9            -- IF THE LAST DIGIT ISN'T A NINE IT IS
0372  A1 09              CMP     #9            -- EASY TO ROUND UP.  JUST ADD A ONE.
0374  26 28              BNE     DECIMAL       --
0376  B6 1C              LDA     HUNDTH        -- BUT IF THE LAST DIGIT IS A NINE CHECK TO
0378  A1 99              CMP     #$99          -- SEE IF IT'S 99.  IF SO IT GETS GRIM.
037A  27 04              BEQ     UGLY          --
037C  AB 07              ADD     #7            -- IF THE NUMBER IS X9 AND X .NE. 9, THEN
037E  20 28              BRA     PCOUT         -- JUST ADD SEVEN TO ROUND UP. DUE TO
                  **                           -- HEXIDECIMAL.
                  **                           -- IF THE LOW TWO DIGITS ARE BOTH NINES
0380  A6 00       UGLY   LDA     #00         --   AND WE NEED TO ROUND UP....
0382  B7 02              STA     PORTC     --     MAKE THE LOW TWO DIGITS BOTH ZEROS
0384  99                SEC               --     AND SET THE CARRY.
                  **
```

```
0385  B6 1B                    LDA     ONEDEG  --       CHECK THE LAST DIGIT AS BEFORE.
0387  A4 09                    AND     #9        --     IF USING THIS PORTION OF THE CODE
0389  A1 09                    CMP     #9          --   THERE HAD TO BE A CARRY.
038B  26 1E                    BNE     NEXT          -- IF THE LAST DIGIT IS NOT A NINE USE THE
038D  B6 1B                    LDA     ONEDEG        -- ADC INSTRUCTION BELOW.
038F  A1 99                    CMP     #$99          -- IF IT IS A NINE, IS THE NEXT ONE A NINE
0391  27 04                    BEQ     RLUGLY        -- ALSO?
0393  AB 07                    ADD     #7          --   IF NOT JUST ADD SEVEN,
0395  20 18                    BRA     PAOUT     --     AND DISPLAY THE OUTPUT.
                       **
0397  A6 00             RLUGLY  LDA     #00       --
0399  B7 00                    STA     PORTA       --   IF SO ROUND UP THE MOST SIGNIFICANT
039B  99                       SEC                 --   DIGIT AND SET EVERYTHING ELSE TO ZERO.
039C  20 13                    BRA     NEXT1     --
                       **
039E  B6 1C             DECIMAL LDA     HUNDTH --
03A0  AB 01                    ADD     #1        --
                       **                           -- THIS IS ALL THAT NEEDS TO BE DONE IF
03A2  B7 02                    STA     PORTC       --   THE LAST DIGIT IS NOT A NINE.
03A4  20 05                    BRA     NEXT      --
                       **
03A6  B6 1C             TRUNC   LDA     HUNDTH  --
03A8  B7 02             PCOUT   STA     PORTC     --  AND IF THERE IS NO CARRY IT'S EVEN EASIER.
03AA  98                       CLC               --
                       **
03AB  B6 1B             NEXT    LDA     ONEDEG
03AD  A9 00                    ADC     #0
03AF  B7 00             PAOUT   STA     PORTA
                       **
03B1  B6 1A             NEXT1   LDA     HUNDEG
03B3  A9 00                    ADC     #0
03B5  B7 01                    STA     PORTB
                       **
03B7  1C 01                    BSET    POSTIV,PORTB
03B9  18 01                    BSET    BLANK,PORTB
03BB  1F 01                    BCLR    DECPT,PORTB
                       **
03BD  81                       RTS
                       **
                       **
                       ********************************************************************************
                       **
                       ** SET UP THE TABLE TO BE USED WITH BCD INCREMENT/DECREMENT ROUTINES.
                       **
                       *       ENDS
                       *       DATA
03BE  00 01 02 03 04   TABLE   FCB     $00,$01,$02,$03,$04,$05,$06,$07,$08,$09
03C3  05 06 07 08 09
03C8  10 11 12 13 14           FCB     $10,$11,$12,$13,$14,$15,$16,$17,$18,$19
03CD  15 16 17 18 19
03D2  20 21 22 23 24           FCB     $20,$21,$22,$23,$24,$25,$26,$27,$28,$29
03D7  25 26 27 28 29
03DC  30 31 32 33 34           FCB     $30,$31,$32,$33,$34,$35,$36,$37,$38,$39
03E1  35 36 37 38 39
03E6  40 41 42 43 44           FCB     $40,$41,$42,$43,$44,$45,$46,$47,$48,$49
03EB  45 46 47 48 49
03F0  50 51 52 53 54           FCB     $50,$51,$52,$53,$54,$55,$56,$57,$58,$59
03F5  55 56 57 58 59
03FA  60 61 62 63 64           FCB     $60,$61,$62,$63,$64,$65,$66,$67,$68,$69
03FF  65 66 67 68 69
0404  70 71 72 73 74           FCB     $70,$71,$72,$73,$74,$75,$76,$77,$78,$79
0409  75 76 77 78 79
040E  80 81 82 83 84           FCB     $80,$81,$82,$83,$84,$85,$86,$87,$88,$89
0413  85 86 87 88 89
0418  90 91 92 93 94           FCB     $90,$91,$92,$93,$94,$95,$96,$97,$98,$99
041D  95 96 97 98 99
```

```
1042                            *       ENDS
1043                            *       CODE
1044                            ********************************************************************************
1045                            **
1046                            **                      SET UP MASK OPTION REGISTER.
1047                            **
1048  0422                              ABSOLUTE
1049                            **
1050                            **
1051  0F38                              ORG     MOR
1052  0F38  07                          FCB     #BIT2+BIT1+BIT0
1053                            **
1054                            **      COMMENTS:
1055                            **      BIT 7   CLOCK SOURCE  0 = CRYSTAL.
1056                            **      BIT 6   TIMER OPTION  0 = INTERNAL.
1057                            **      BIT 5   TIMER/CLOCK SOURCE  0 = INTERNAL.
1058                            **      BIT 4   NOT USED.
1059                            **      BIT 3   NOT USED.
1060                            **      BIT 2   SET  -
1061                            **      BIT 1   SET    -  PRESCALE SELECT  111 => 128
1062                            **      BIT 0   SET  -
1063                            **
1064                            **
1065                            ********************************************************************************
1066                            **
1067                            **                        ASSIGN INTERRUPT VECTORS.
1068                            **
1069  0FF8                              ORG     INTRPT
1070                            **
1071  0FF8  012E                        FDB     BLINK   TIMER/INT2 INTERRUPT VECTOR.
1072  0FFA  014D                        FDB     COUNT   EXTERNAL INTERRUPT VECTOR.
1073  0FFC  014D                        FDB     COUNT   SOFTWARE INTERRUPT VECTOR, NOT USED.
1074  0FFE  0080                        FDB     RESTRT  RESET VECTOR.
1075                            **
1076                            **
1077                            **
1078                                    ENDS
1079  1000                              END


        Lines Assembled :  1079           Assembly Errors :  0
```

C. TILT

```
1                               TTL                     POSITION DETERMINING PROGRAM (ELEVATION)
2                       *                       LATEST REVISION             9 MAY 89
3                       *                       FILE NAME                   TILT.ASM
4                       **
5                       ** PROGRAM DESCRIPTION
6                       **
7                       **
8                       **
9                       ** I/O REGISTER ADDRESSES
10                      **
11      0000            PORTA   EQU     $0000   I/O PORT A
12      0001            PORTB   EQU     $0001   I/O PORT B
13      0002            PORTC   EQU     $0002   I/O PORT C
14      0003            PORTD   EQU     $0003   INPUT PORT D
15                      **
16                      ** DATA DIRECTION REGISTER OFFSET
17                      **
18      0004            DDR     EQU     4       (eg. DDR FOR PORT A IS  PORTA+DDR )
19                      **
20                      ** OTHERS
21                      **
22      0008            TIMER   EQU     $0008   EIGHT BIT TIMER REGISTER.
23      0009            TCR     EQU     $0009   TIMER CONTROL REGISTER.
24      000A            MR      EQU     $000A   MISCELLANEOUS REGISTER.
25      0010            RAM     EQU     $0010   START OF ON-CHIP RAM(112 - 31 FOR STACK)
26      0080            ZROM    EQU     $0080   PAGE ZERO OF ROM.
27      0100            ROM     EQU     $0100   START OF MAIN ROM.
28      0F38            MOR     EQU     $0F38   MASK OPTION REGISTER.
29      0FF8            INTRPT  EQU     $0FF8   LOCATION OF INTERRUPT VECTORS.
30      1000            MEMSIZ  EQU     $1000   MEMORY ADDRESS SIZE.
31                      **
32                      ** EQUATES
33                      **
34      0001            BIT0    EQU     1
35      0002            BIT1    EQU     2
36      0004            BIT2    EQU     4
37      0008            BIT3    EQU     8
38      0010            BIT4    EQU     16
39      0020            BIT5    EQU     32
40      0040            BIT6    EQU     64
41      0080            BIT7    EQU     128
42                      **
43      0000            B0      EQU     0
44      0001            B1      EQU     1
45      0002            B2      EQU     2
46      0003            B3      EQU     3
47      0004            B4      EQU     4
48      0005            B5      EQU     5
49      0006            B6      EQU     6
50      0007            B7      EQU     7
51                      **
52                      ** EQUATES FOR THE TIMER CONTROL REGISTER
53                      **
54                      ***
55      0007            TIR     EQU     7       TIMER INTERRUPT REQUEST. 1 = REQUEST, 0 = NO REQ.
56      0006            TIM     EQU     6       TIMER INTERRUPT MASK. 1 = DISABLED, 0 = ENABLED.
57      0005            TIN     EQU     5       EXTERNAL OR INTERNAL CLOCK SOURCE. 1 = EXT, 0 = INT.
58      0004            TEE     EQU     4       EXTERNAL CLOCK ENABLE. NOT USED.
59      0003            PSC     EQU     3       PRESCALER CLEAR. NOT USED.
60      0002            PS2     EQU     2       (PS2)  --
61      0001            PS1     EQU     1       (PS1)    |--  PRESCALER SELECT BITS.
```

```
0000            PS0     EQU     0       (PS0) --
                **
                ** EQUATES FOR THE STATUS BYTE, 'STAT'.
                ***
                ***
                **
0007            UD      EQU     7       COUNT DIRECTION?  1 = UP, 0 = DOWN.
0006            MOD_32  EQU     6       IS 'BINCT' MODULO 32?   1 = YES, 0 = NO.
0005            FLASH   EQU     5       BLINK THE DISPLAY?  1 = YES, 0 = NO.
0004            POSCT   EQU     4       DISPLAY POSITION OR COUNT?  1 = POS, 0 = COUNT.
0003            L_SET   EQU     3       VALUE OF 'MODE,PORTD' LAST TIME.
0002            NEGTIV  EQU     2       IS 'BCDCT'NEGATIVE NUMBER?  1 = YES, 0 = NO.
                ***             1       NOT USED.
                ***             0       NOT USED.
                ***
                ***
                ** I/O EQUATES AND DESCRIPTIONS.
                ***
                ***
                ***      PORT A  (I/O)
                ***
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                ***     |          BCD DIGIT #4         |         BCD DIGIT #3          |
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                ***     |   D4  |   C4  |   B4  |   A4  |   D3  |   C3  |   B3  |   A3  |
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                *** BIT      7       6       5       4       3       2       1       0
                ***
                ***
                ***      PORT B  (I/O)
                ***
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                ***     |        DISPLAY CONTROL        |           NOT USED            |
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                ***     | DECPT | POSTIV|       | BLANK |       |       |       |       |
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                *** BIT      7       6       5       4       3       2       1       0
                ***
0007            DECPT   EQU     7       TO DISPLAY THE DECIMAL POINT...DECPT IS CLEARED
0006            POSTIV  EQU     6       USED TO DISPLAY NEGATIVE SIGN...CLEARED TO SHOW
                ***                     MINUS SIGN.
0004            BLANK   EQU     4       TO BLANK DIGITS 2 AND 3...CLEAR BLANK.
                ***                     DIGITS 4 AND 5 ARE ALWAYS BLANKED.
                ***                     DIGIT 1 IS NEVER BLANKED.
                ***
                ***      PORT C  (I/O)
                ***
                ***     +-------+-------+-------+-------+-------+-------+-------+-------+
                ***     |          BCD DIGIT #2         |BCD DIGIT #1(LEAST SIGNIFICANT)|
                ***     +-------+-------+-------+-------+-------+-------+-------+------ +
                ***     |   D2  |   C2  |   B2  |   A2  |   D1  |   C1  |   B1  |   A1  |
                ***     +-------+-------+-------+-------+-------+-------+-------+------ +
                *** BIT      7       6       5       4       3       2       1       0
                ***
                ***
                ***      PORT D  (INPUT ONLY)
                ***
                ***     +-------+-------+-------+-------+-------+-------+-------+------ +
                ***     | CH_A  |  INT2 |  CH_B | FUNCT |  SET  |       |       |       |
                ***     +-------+-------+-------+-------+-------+-------+-------+------ +
                *** BIT      7       6       5       4       3       2       1       0
                ***
0007            CH_A    EQU     7       INDICATES THE STATUS OF CHANNEL A.
0006            INT2    EQU     6       INTERRUPT #2.  USED TO CHANGE DISPLAY MODES.
0005            CH_B    EQU     5       INDICATES THE STATUS OF CHANNEL B.
0004            FUNCT   EQU     4       USED TO PUT THE PROGRAM IN A MODE THAT WILL ALLOW
```

```
128                     ***                     'HYST' TO BE INCREMENTED.
129     0003    SET     EQU     3       INCREMENTS 'HYST' WHEN TOGGLED AND FUNCT IS LOW.
130                     ***
131                     ***
132                     ********************************************************************************
133                     **                                                                              *
134                     **                          RAM VARIABLES                                       *
135                     **                                                                              *
136                     ********************************************************************************
137                     **
138                     ** RESERVE MEMORY SPACE FOR THE PROGRAM VARIABLES.
139                     **
140 0000                        DATA
141                     **
142                     **
143 0000                        ABSOLUTE (ABSOLUTE ADDRESSING USED HERE TO RELATIVE DIRECTIVE)
144                     **
145 0010                        ORG     RAM     START OF RAM.
146                     **
147                     *** BINARY COUNT.
148 0010                BINCT   RMB     2
149     0010            HIBIN   EQU     BINCT   HI BYTE.
150     0011            LOBIN   EQU     BINCT+1 LO BYTE.
151                     **
152                     *** POSITION POINTERS.
153 0012                PTR     RMB     3       EACH BYTE POINTS TO A POSITION IN THE
154                     **                      TABLE THAT CONTAINS ONE OR TWO DIGITS
155                     **                      OF THE BCD POSITION.
156     0012            PTR3    EQU       PTR   MOST SIGNIFICANT DIGITS.
157     0013            PTR2    EQU       PTR+1
158     0014            PTR1    EQU       PTR+2 LEAST SIGNIFICANT DIGIT.
159                     **                              .
160                     *** COUNT POINTERS.
161 0015                CTPTR   RMB     2       EACH BYTE POINTS TO A POSITION IN THE
162                     **                      TABLE THAT CONTAINS TWO OF THE DIGITS
163                     **                      IN THE BCD COUNT.
164     0015            CTPTR2  EQU     CTPTR   MOST SIGNIFICANT DIGITS.
165     0016            CTPTR1  EQU     CTPTR+1 LEAST SIGNIFICANT DIGITS.
166                     **
167                     *** BCD POSITION IN DEGREES.
168 0017                DEGRES  RMB     3
169     0017            ONEDEG  EQU     DEGRES      CONTENTS X   1.000
170     0018            HUNDTH  EQU     DEGRES+1    CONTENTS X   0.010
171     0019            THOUTH  EQU     DEGRES+2  + CONTENTS X   0.001
172                     ***                       --------------------
173                     ***                         POSITION IN DEGREES
174                     **
175                     *** BCD COUNT.
176 001A                BCDCT   RMB     2
177     001A            HUNDRD  EQU     BCDCT       CONTENTS X    100
178     001B            TENONE  EQU     BCDCT+1   + CONTENTS X      1
179                     ***                       ----------------------
180                     ***                       NUMBER OF PULSES COUNTED
181                     ***
182                     *** HYSTERESIS COUNTER. POINTS TO A NUMBER IN THE TABLE THAT IS THE
183                     ***     AMOUNT OF HYSTERESIS PRESENT IN THE SYSTEM.  INITIALIZED TO 6.
184 001C                HYSTPT  RMB     1
185                     **
186                     *** POSITION INCREMENT.  CONTAINS A NUMBER, THAT WHEN MULTIPLIED BY 0.001
187                     ***     IS THE NUMBER OF DEGREES THAT THE POSITION COUNTER (BCDPOS) IS
188                     ***     TO BE INCREMENTED OR DECREMENTED DURING PROGRAM EXECUTION.
189                     ***     THE VALUE OF 'POSINC', DETERMINED EXPERIMENTALLY, SHOULD BE
190                     ***     7.0452.  SINCE THE PROGRAM IS DESIGNED WORK WITH INTEGERS ONLY
191                     ***     THIS NUMBER IS ROUNDED TO 7.  TO REDUCE THE CUMULATIVE EFFECT OF
192                     ***     THE ROUND OFF, EVERY 32 COUNTS 'POSINC' IS SET EQUAL TO 8.  THIS
193                     ***     AGAIN LEADS TO SOME CUMULATIVE ERROR, BUT THE SMALL ANGULAR RANGE
```

```
194                     ***     OF THE TILT ANGLE (10.5 DEGREES) ALLOWS US TO NEGLECT ANY FURTHER
195                     ***     MODIFICATIONS.
196                     ***
197   001D              POSINC  RMB     1
198                     ***
199                     *** HYSTERESIS VARIABLES.  USED TO ELIMINATE THE EFFECTS OF BACKLASH ON
200                     ***     THE POSITION MEASUREMENTS.
201                     ***
202   001E              HYST    RMB     1       THE THRESHHOLD VALUE DETERMINED
203                     ***                     EXPERIMENTALLY.
204   001F              HYSTCT  RMB     1       CURRENT AMOUNT OF HYSTERESIS MEASURED.
205                     ***
206                     *** STATUS BYTE.  USED TO KEEP TRACK OF WHAT IS GOING ON.
207                     ***
208   0020              STAT    RMB     1       CURRENT STATUS.
209   0021              LSTAT   RMB     1       PREVIOUS/LAST STATUS.  USED TO KEEP TRACK OF
210                     ***                     L_SET ONLY.
211                     ***
212                     *** TIMER COUNTER.  USED IN CONJUNCTION WITH THE TIMER PRESCALER AND THE
213                     ***     TDR TO KEEP TRACK OF ONE SEC. INTERVALS.  USED IN BLINKING THE
214                     ***     DISPLAY.  INITIALLY SET TO 31, WHEN THE 'FLASH' BIT OF 'STAT'
215                     ***     IS SET.  TIMCT IS DECREMENTED EACH CLOCK INTERRUPT (APPROX. 31
216                     ***     TIMES PER SEC).  RESET TO 31 WHEN CONTENTS GO TO ZERO.
217                     ***     WHEN (TIMCT)=0 THE DISPLAY WILL TOGGLE.
218                     ***
219   0022              TIMCT   RMB     1
220                     **
221                             ENDS
222                     **
223                     ***
224                     ********************************************************************************
225                     **                                                                              *
226                     **                          PAGE ZERO ROM
227                     **                                                                              *
228                     ********************************************************************************
229                     **
230                     **                      INITIALIZATION ROUTINE.
231                     **
232                     **
233   0000                      CODE
234                     **
235   0080                      ORG     ZROM    PAGE ZERO ROM.
236                     **
237   0080                      RELATIVE        RELATIVE ADDRESSING MUST BE USED FOR THE BRANCH.
238                     **
239         0080        RESTRT  EQU     $       THIS IS THE ENTRY POINT WHEN AN EXTERNAL
240                     ***                     INTTERRUPT OCCURS.
241                     **
242                     ********************************************************************************
243                     **
244                     ***             INITIALIZE THE PC AND CLEAR RAM.
245                     ***
246                     ***
247   0080  9B                  SEI             SET INTERUPT TO AVOID INTERUPTION AND
248   0081  9C                  RSP             RESET THE STACK POINTER. JUST IN CASE!
249                     ***
250   0082  AE 10               LDX     #BINCT  CLEAR ALL OF THE VARIABLES BETWEEN
251   0084  7F          CLRIT   CLR     ,X      'BINCT' AND 'TIMCT' (INCLUSIVE).NOTE
252   0085  5C                  INCX            THAT THIS SETS THE COUNTER AND THE POS-
253   0086  A3 22               CPX     #TIMCT  ITION TO ZERO. THIS MEANS THAT ROTATION
254   0088  23 FA               BLS     CLRIT   SHOULD START IN AN INCREASING (CW)
255                     ***                     DIRECTION FROM THE MOST CCW POSITION
256                     ***                     AFTER A RESET.
257                     ***
258   008A                      ABSOLUTE        BACK TO ABSOLUTE ADDRESSING.
259                     ***
```

```
                        ********************************************************************************
                        ***
                        ***                          ESTABLISH I/O PORTS.
                        ***
008A  A6 FF                     LDA     #-1         PORTS A,B,C ARE CONFIGURED AS
008C  B7 04                     STA     PORTA+DDR   ALL OUTPUT. PORT D IS ALL INPUT
008E  B7 05                     STA     PORTB+DDR   SO THERE IS NO MASK TO SET.
0090  B7 06                     STA     PORTC+DDR
                        ***
                        ********************************************************************************
                        ***                  SET UP THE STATUS REGISTER.
                        ***
0092  A6 08                     LDA     #%00001000  --
0094  B4 03                     AND     PORTD         |--> SET UP 'L_SET' BIT OF 'STAT'.
0096  B7 20                     STA     STAT        --
                        ***
0098  1C 20                     BSET    MOD_32,STAT  0 IS MODULO 32.
                        **
                        ********************************************************************************
                        ***
                        ***                     INITIALIZE HYSTCT.
                        ***
009A  A6 06                     LDA     #06
009C  B7 1E                     STA     HYST
009E  B7 1C                     STA     HYSTPT
                        ***
                        ********************************************************************************
                        **
                        **        SET UP THE TIMER FOR A 4 MHZ CRYSTAL / 4 = 1 MHZ CLOCK.
                        ***
                        ***    NOTE:  THE MASK OPTION REGISTER IS IN ROM.  IT IS SET UP AT
                        ***           THE END OF THE PROGRAM.
                        ***                              .
                        **********************   SET UP THE TCR.  *********************************
                        ***
00A0  A6 47                     LDA       #BIT6+BIT2+BIT1+BIT0
                        ***              (TIM)|(PS2)(PS1)(PS0)
                        ***(DISABLE INTERRUPT)|(PRESCALE BY 128)
                        ***
00A2  B7 09                     STA     TCR
                        ***
                        ***
                        *** SET UP THE TIMER.
                        ***
00A4  A6 FF                     LDA     #255    1 MHZ/(128*255) = 30.6 (APPROX. 31)
00A6  B7 08                     STA TIMER
                        ***
                        ***************  INITIALIZE THE TIMER COUNTER.  ***********************
                        ***
00A8  A6 1F                     LDA     #31     PROVIDES FOR 1 SEC. BLINK INTERVAL.
00AA  B7 22                     STA     TIMCT   FOR 2 SEC. INTERVAL JUST USE TIMECT=62, etc.
                        ***
                        ***
                        ********************************************************************************
                        **
                        **                      SET UP MISCELLANEOUS REGISTER.
                        **
00AC  1D 0A                    BCLR    B6,MR    ENABLES THE SECOND INTERRUPT.
                        **
                        ********************************************************************************
                        **
                        **                   COUNT = 0 IS DISPLAYED INITIALLY.
                        **
00AE  CD 02 D8                  JSR     OUTCT
00B1  1C 01                     BSET    POSTIV,PORTB
                        **
```

```
326                             **
327   00B3   9A                        CLI             CLEAR THE INTERRUPT MASK TO GET STARTED.
328                             ***
329   00B4                      RELATIVE              RELATIVE ADDRESSING MUST BE USED FOR THE
330                             ***                   REMAINDER OF THE PROGRAM.
331                             ***
332                             ********************************************************************************
333                             **
334                             ** WAIT LOOP.  EXECUTES, UNTIL AN INTERRUPT OCCURS.
335                             **
336   00B4   09 03 0B           PAUSE   BRCLR   FUNCT,PORTD,CHHYST WANT TO CHANGE HYST?
337                             **                                YES...GO TO CHHYST.
338   00B7   06 03 04                   BRSET   SET,PORTD,SBIT    NO...'SET,PORTD' SET?
339   00BA   17 20                      BCLR    L_SET,STAT            NO...CLEAR 'L_SET,STAT'
340   00BC   20 F6                      BRA     PAUSE                   AND LOOP.
341   00BE   16 20              SBIT    BSET    L_SET,STAT            YES...SET 'L_SET,STAT'
342   00C0   20 F2                      BRA     PAUSE                   AND LOOP.
343                             **
344                             ********************************************************************************
345                             **
346                             ** HYSTERESIS MODIFICATION ROUTINE.  PERMITS MODIFICATION OF THE
347                             ** HYSTERESIS BUFFER WITHOUT REPROGRAMMING.
348                             **                                YES...
349   00C2   A6 40              CHHYST  LDA     #BIT6             DISABLE TIMER INTERRUPT.
350   00C4   B7 09                      STA     TCR
351                             ***
352   00C6   A6 08                      LDA     #%00001000        SAVE 'L_SET'
353   00C8   B4 20                      AND     STAT              INTO
354   00CA   B7 21                      STA     LSTAT             'LSTAT'.
355   00CC   A6 08                      LDA     #%00001000
356   00CE   B4 03                      AND     PORTD             'SET,PORTD' --> ACCUMULATOR
357   00D0   B1 21                      CMP     LSTAT             HAS THE SET SWITCH BEEN CHANGED?
358   00D2   27 15                      BEQ     DISPLA
359                             ***                               YES...
360   00D4   A6 08                      LDA     #%00001000        --
361   00D6   B8 20                      EOR     STAT                |-->CHANGE 'L_SET,STAT',
362   00D8   B7 20                      STA     STAT              --
363   00DA   3C 1E                      INC     HYST              THEN INCREMENT THE HYSTERESIS
364   00DC   3C 1C                      INC     HYSTPT            POINTER AND 'HYST'...
365                             ***
366   00DE   B6 1C                      LDA     HYSTPT          --
367   00E0   A1 19                      CMP     #25               --
368   00E2   23 05                      BLS     DISPLA               --
369                             ***                                   -- BUT NOT ABOVE 25.
370   00E4   4F                         CLRA                        --       THEN--->|
371   00E5   B7 1E                      STA     HYST              --                 |
372   00E7   B7 1C                      STA     HYSTPT          --                   |
373                             ***                                                  |
374   00E9   A6 00              DISPLA  LDA     #%00000000        NO... JUST--------->|
375   00EB   B7 00                      STA     PORTA           --                   |
376   00ED   A6 C0                      LDA     #%11000000        --                 |
377   00EF   B7 01                      STA     PORTB                --             \|/
378                             ***                                    -- DISPLAY CURRENT 'HYST'.
379   00F1   BE 1C                      LDX     HYSTPT               --
380   00F3   D6 03 28                   LDA     TABLE,X            --
381   00F6   B7 02                      STA     PORTC           --
382                             ***                               IS 'HYST' SETTING COMPLETE?
383   00F8   09 03 C7                   BRCLR   FUNCT,PORTD,CHHYST NO... KEEP CHECKING 'SET'.
384   00FB   04 20 04                   BRSET   NEGTIV,STAT,SIGN   YES... RESET THE DISPLAY.
385   00FE   1C 01                      BSET    POSTIV,PORTB
386   0100   20 02                      BRA     DIR
387   0102   1D 01              SIGN    BCLR    POSTIV,PORTB
388   0104   08 20 05           DIR     BRSET   POSCT,STAT,SHOPOS
389                             **
390   0107   CD 02 D8                   JSR     OUTCT
391   010A   20 03                      BRA     DUNCHG
```

```
392                             ***
393   010C  CD 02 E5    SHOPOS  JSR     OUTPOS
394                             ***
395   010F  0B 20 04    DUNCHG  BRCLR   FLASH,STAT,NO_INT  IF THE DISPLAY IS TO BLINK...
396   0112  A6 07                LDA     #BIT2+BIT1+BIT0    ENABLE TIMER INTERRUPT AND RESET
397   0114  B7 09                STA     TCR                TIMER PRESCALER
398   0116  20 9C    NO_INT  BRA     PAUSE              PRIOR TO RETURNING.
399                             ***
400                             **
401                             ********************************************************************************
402                             ** MAXIMUM EXECUTION TIME FOR THE REMAINDER OF THE PROGRAM OCCURS
403                             ** IF THE COUNTER ROTATES THROUGH ZERO AS THE DISPLAY MODE IS CHANGED
404                             ** FROM THE BLINKING MODE TO THE COUNT MODE AT THE SAME TIME THAT THE
405                             ** BLINKING ROUTINE IS CAUSING THE DISPLAY TO TOGGLE TO SHOW THE
406                             ** POSITION IN DEGREES.
407                             **     MAXIMUM EXECUTION TIME = 67 + 140 + 618 = 825 CLOCK CYCLES.
408                             **
409                             ********************************************************************************
410                             **
411                             **MODE CHANGE ROUTINE.  CHANGES THE DISPLAY MODE FROM
412                             **       COUNT -> POSITION -> BLINKING -> COUNT ->....(ETC.)
413                             **       MAXIMUM EXECUTION TIME OF 127 CLOCK CYCLES OCCURS WHEN THE
414                             **       DISPLAY MODE IS CHANGED FROM DISPLAYING THE COUNT TO DISPLAYING
415                             **       THE POSITION (IN DEGREES).
416                             **       IF THE DISPLAY IS CHANGED FROM BLINKING TO A COUNT DISPLAY
417                             **       EXECUTION TIME IS 67 CLOCK CYCLES.
418                             **
419   0118  1F 0A      CHMODE  BCLR    B7,MR              AVOID REPEATED INTERRUPTS.
420                             **
421   011A  0A 20 10            BRSET   FLASH,STAT,DIS_CT  IF FLASHING, DISPLAY COUNT...
422   011D  09 20 07            BRCLR   POSCT,STAT,DISPOS  IF SHOWING COUNT, DISPLAY POSITION...
423   0120  1A 20              BSET    FLASH,STAT         ELSE, BLINK.
424                             **
425   0122  A6 07              LDA     #BIT2+BIT1+BIT0    ENABLE TIMER INTERRUPT AND RESET
426   0124  B7 09              STA     TCR                TIMER PRESCALER.
427   0126  80                RTI
428                             **
429   0127  18 20      DISPOS  BSET    POSCT,STAT      --
430   0129  CD 02 E5           JSR     OUTPOS            |-- DISPLAY CURRENT POSITION, AND WAIT.
431   012C  80                RTI                     --
432                             **
433   012D  A6 47      DIS_CT  LDA     #BIT6+BIT2+BIT1+BIT0  DISABLE TIMER INTERRUPT AND RESET
434   012F  B7 09              STA     TCR                   TIMER PRESCALER.
435   0131  19 20              BCLR    POSCT,STAT      --
436   0133  1B 20              BCLR    FLASH,STAT        |
437                             **                        |-- DISPLAY CURRENT COUNT, AND WAIT.
438   0135  CD 02 D8           JSR     OUTCT             |
439   0138  80                RTI                     --
440                             **
441                             ********************************************************************************
442                             **
443                             ** BLINK ROUTINE.  INTERRUPT ROUTINE TO CHANGE THE DISPLAY FROM POSITION
444                             **       TO COUNT OR VICE VERSA EVERY 31 ST TIMER INTERRUPT IF THE
445                             **       'FLASH' BIT OF 'STAT' IS SET.
446                             **       MAXIMUM EXECUTION TIME OF 140 CLOCK CYCLES OCCURS WHEN THE
447                             **       DISPLAY IS TOGGLED FROM A COUNT DISPLAY TO A POSITION DISPLAY.
448                             **
449         0139      BLINK   EQU     $
450   0139  0F 09 DC          BRCLR   TIR,TCR,CHMODE      IF THE INTERRUPT WAS NOT A TIMER
451                             **                        INTERRUPT IT MUST BE FROM INT2.
452                             **
453   013C  1F 09              BCLR    TIR,TCR            AVOID REPEATED TIMER INTERRUPTS.
454                             **
455   013E  3A 22              DEC     TIMCT              IF THERE HAVE BEEN 31 TIMER
456   0140  27 01              BEQ     CHGDIS             INTERRUPTS  (1 SEC), IT'S TIME TO
457                             **                        CHANGE THE DISPLAY.
```

```
0142  80                    RTI                          OTHERWISE, IT'S BACK TO WORK.
                      **
0143  A6 1F           CHGDIS LDA    #31                  RESET TIMCT TO 31 (1 SEC. INTERVAL).
0145  B7 22                 STA    TIMCT
                      **
0147  B6 20                 LDA    STAT          --
0149  A8 10                 EOR    #%00010000      |-- CHANGE 'POSCT' BIT OF 'STAT'.
014B  B7 20                 STA    STAT          --
                      **
014D  08 20 04              BRSET  POSCT,STAT,POSOUT    DECIDE ON CORRECT DISPLAY.
                      **
                      ************ CHANGE THE DISPLAY TO SHOW THE COUNT..... **************
                      **
0150  CD 02 D8              JSR    OUTCT
0153  80                    RTI
                      **
                      ************ OR HAVE THE DISPLAY SHOW THE POSITION. ******************
                      **
0154  CD 02 E5       POSOUT JSR    OUTPOS
0157  80                    RTI
                      **
                      ********************************************************************************
                      **
                      **                          COUNT ROUTINE.
                      **        WHEN A COUNT IS RECEIVED THIS IS THE ENTRY POINT .
                      **        MAXIMUM EXECUTION TIME OF 618 CLOCK CYCLES OCCURS WHEN THE
                      **        COUNTER ROTATES CCW THROUGH ZERO AND THE POSITION (IN DEGREES)
                      **        IS BEING DISPLAYED.
                      **
                      **
                      ** CURRENT DIRECTION OF ROTATION IS DETERMINED BY INSPECTING THE STATUS
                      ** OF 'CH_A' AND 'CH_B'.  THE FOUR POSSIBILITIES AND THE ASSOCIATED
                      ** DIRECTION OF ROTATION ARE AS SHOWN BELOW.  NOTE THAT THIS SCHEME
                      ** PREVENTS MULTIPLE OSCILLATIONS ABOUT A SINGLE POINT FROM
                      ** REPEATEDLY INCREMENTING OR DECREMENTING THE COUNTER.
                      **
                      **   +--------+--------+-----------------+------------------+
                      **   |  CH_A  |  CH_B  |    DIRECTION    |  COUNT THE PULSE? |
                      **   |        |        |  OF ROTATION    |                   |
                      **   +--------+--------+-----------------+------------------+
                      **   |   LO   |   LO   |       CW        |        NO         |
                      **   |   LO   |   HI   |      CCW        |        YES        |
                      **   |   HI   |   LO   |      CCW        |        NO         |
                      **   |   HI   |   HI   |       CW        |        YES        |
                      **   +--------+--------+-----------------+------------------+
                      **
                      ******** FIRST SEE IF WE ARE SUPPOSED TO COUNT THIS INTERUPT. ********
                      **
0158                  COUNT  EQU    $
0158  0A 03 01              BRSET  CH_B,PORTD,OKCT     IF CH_B IS LO WE DON'T COUNT THE
015B  80                    RTI                        INTERRUPT.
                      **
                      ************** IF THE INTERRUPT IS VALID UPDATE 'STAT'. **************
                      **
015C  A6 7F           OKCT  LDA    #%01111111
015E  B4 20                 AND    STAT           SAVE ALL OF THE OLD 'STAT' EXCEPT THE
0160  B7 20                 STA    STAT           DIRECTION OF ROTATION.
0162  A6 80                 LDA    #%10000000
0164  B4 03                 AND    PORTD          'CH_A,PORTD' INDICATES THE DIRECTION
                      *                           OF ROTATION AND BECOMES 'UD,STAT'.
0166  BA 20                 ORA    STAT           ADD THE RESULTS TO GET
0168  B7 20                 STA    STAT           THE NEW 'STAT'.
                      **
                      ** DECIDE IF THE "SLACK" DUE TO BACKLASH/HYSTERESIS HAS BEEN TAKEN OUT.
                      **
016A  0E 20 09              BRSET  UD,STAT,HYSTCK  IF ROTATING CW SEE BELOW.
```

```
016D  B6 1F           LDA     HYSTCT          ELSE, SEE IF WE DECREMENT THIS TIME.
016F  27 4B           BEQ     CCW             IF HYSTCT=0, GO TO THE COUNT DOWN
                    **                        ROUTINE.
0171  A0 01           SUB     #1              ELSE, DECREMENT THE HYSTERESIS COUNTER,
0173  B7 1F           STA     HYSTCT
0175  80              RTI                     AND WAIT FOR THE NEXT INTERRUPT.
                    **
0176  B6 1E          HYSTCK  LDA     HYST            IF ROTATING CW....
0178  B1 1F                  CMP     HYSTCT          AND  HYST = HYSTCT ....
017A  27 03                  BEQ     CW              COUNT THE PULSE .
017C  3C 1F                  INC     HYSTCT          ELSE, INCREMENT THE HYSTERESIS COUNTER,
017E  80                     RTI                     AND WAIT FOR ANOTHER PULSE.
                    **
                    **
                    ********************************************************************************
                    **
                    **                          CLOCKWISE ROUTINE.
                    **
017F                CW      EQU     $
                    **
                    ***
                    **************  INCREMENT THE BINARY COUNTER (BINCT).  *****************
                    ***
0181  B6 11                 LDA     LOBIN   BEGIN AT THE LSB OF THE BINARY COUNTER.
0183  AB 01                 ADD     #1      LOBIN = LOBIN + 1 ; CARRY -> C,CCR
0185  B7 11                 STA     LOBIN
                    ***
0187  B6 10                 LDA     HIBIN
0189  A9 00                 ADC     #0              ADD THE CARRY TO THE HIGH BYTE.
018B  B7 10                 STA     HIBIN
                    ***
                    ***
                    ******************  CLR/SET MOD_32 APPROPRIATELY.  **********************
                    ***                             .
018D  B6 11                 LDA     LOBIN       IF THE LOW FIVE BITS OF 'LOBIN' ARE NOT
018F  A4 1F                 AND     #%00011111  NOT THEN THE NUMBER ISN'T A MODULO 32 NUMBER.
0191  26 04                 BNE     NOT_32
                    ***
0193  1C 20                 BSET    MOD_32,STAT
0195  20 02                 BRA     DIRCHK
                    ***
0197  1D 20          NOT_32 BCLR    MOD_32,STAT
                    ***
                    ***
0199  B6 10          DIRCHK LDA     HIBIN
019B  2B 19                 BMI     CWNEG           IF HIBIN < 0 , WE'RE ROTATING CW TOWARD
                    ***                             THE ORIGIN.
                    ***
019D  26 10                 BNE     CWPOS           ELSE IF BINCT .NE. 0 ,
019F  B6 11                 LDA     LOBIN           WE'RE ROTATING CW
01A1  26 0C                 BNE     CWPOS           AWAY FROM THE ORIGIN.
                    ***
01A3  15 20                 BCLR    NEGTIV,STAT     ELSE, WE'VE GONE THROUGH ORIGIN IN CW
                    ***                             DIRECTION.  CLR NEGATIVE SIGN.
01A5  AE 12                 LDX     #PTR3   --
01A7  7F              CLRIT2 CLR    ,X        --
01A8  5C                     INCX                --RESET ALL COUNTERS AND DEGRES TO ZERO.
01A9  A3 19                  CPX     #THOUTH   --
01AB  23 FA                  BLS     CLRIT2  --
01AD  20 4C                  BRA     UPOUT           UPDATE OUTPUT.
                    ***
01AF  AD 5E           CWPOS  BSR     ADDBCD
01B1  CD 02 32               JSR     INCPOS
01B4  20 45                  BRA     UPOUT
                    ***
01B6  CD 02 7A        CWNEG  JSR     SUBBCD
```

```
590   01B7   CD 02 9A            JSR     DECPOS
591   01BA   20 3D               BRA     UPOUT
592                      ***
593                      **
594                      ********************************************************************************
595                      **
596                      **                    COUNTER-CLOCKWISE ROUTINE.
597                      **
598          01BC        CCW     EQU     $
599                      **
600                      ***
601                      ******************  CLR/SET MOD_32 APPROPRIATELY.  ********************
602                      ***
603   01BC   B6 11               LDA     LOBIN         IF THE LOW FIVE BITS OF 'LOBIN' ARE NOT
604   01BE   A4 1F               AND     #%00011111    ZERO THEN THE NUMBER ISN'T A MODULO 32 NUMBER.
605   01C0   26 04               BNE     NO_32
606                      ***
607   01C2   1C 20               BSET    MOD_32,STAT
608   01C4   20 02               BRA     DECBIN
609                      ***
610   01C6   1D 20       NO_32   BCLR    MOD_32,STAT
611                      ***
612                      ***
613                      ***************  DECREMENT THE BINARY COUNTER (BINCT).  ***************
614                      ***
615   01C8   B6 11       DECBIN  LDA     LOBIN    BEGIN AT THE LSB OF THE BINARY COUNTER.
616   01CA   A0 01               SUB     #1       LOBIN = LOBIN - 1 ; BORROW -> C,CCR
617   01CC   B7 11               STA     LOBIN
618                      ***
619   01CE   B6 10               LDA     HIBIN
620   01D0   A2 00               SBC     #0       SUBTRACT THE CARRY FROM THE HIGH BYTE.
621   01D2   B7 10               STA     HIBIN
622                      ***
623   01D4   B6 10               LDA     HIBIN
624   01D6   2A 1B               BPL     CCWPOS         IF HIBIN .GE. 0 , WE'RE ROTATING CCW TOWARD
625                      ***                             THE ORIGIN.
626   01D8   A1 FF               CMP     #-1       --
627   01DA   26 10               BNE     CCWNEG      --  ELSE IF BINCT .NE. -1 ,
628   01DC   B6 11               LDA     LOBIN         --WE'RE ROTATING CCW AWAY
629   01DE   A1 FF               CMP     #-1         --  FROM THE ORIGIN.
630   01E0   26 0A               BNE     CCWNEG    --
631   01E2   14 20               BSET    NEGTIV,STAT    ELSE, WE'VE GONE THROUGH ORIGIN IN CCW
632                      ***                             DIRECTION.  SET NEGATIVE SIGN.
633                      ***                             AND SET ALL COUNTERS APPROPRIATELY.
634   01E4   AE 12               LDX     #PTR3     --
635   01E6   7F          CLREM   CLR     ,X          --
636   01E7   5C                  INCX                  -- RESET ALL COUNTERS AND DEGRES TO ZERO.
637   01E8   A3 19               CPX     #THOUTH   --
638   01EA   23 FA               BLS     CLREM     --
639                      ***
640   01EC   AD 1F       CCWNEG  BSR     ADDBCD
641   01EE   CD 02 32            JSR     INCPOS
642   01F1   20 06               BRA     UPOUT
643                      ***
644   01F3   CD 02 7A    CCWPOS  JSR     SUBBCD
645   01F6   CD 02 9A            JSR     DECPOS
646                      ***
647                      ***
648                      **
649                      ********************************************************************************
650                      **
651                      ** OUTPUT ROUTINE. ROUTINE TO PRINT DATA TO THE OUTPUT PORTS.  BY
652                      **       CALLING THE APPROPRIATE SUBROUTINE.('OUTCT' TO OUTPUT THE
653                      **       THE COUNT AND 'OUTPOS' TO OUTPUT THE POSITION).
654                      **
655          01F9        UPOUT   EQU     $
```

```
                        **
01F9  04 20 04          BRSET   NEGTIV,STAT,MINUS  --
01FC  1C 01             BSET    POSTIV,PORTB         --
01FE  20 02             BRA     DISCHK                 --
                        **                               --    SET THE NEGATIVE SIGN
0200  1D 01             MINUS   BCLR    POSTIV,PORTB       --      APPROPRIATELY.
                        **
0202  09 20 04          DISCHK  BRCLR   POSCT,STAT,PUTCT
                        **
0205  CD 02 E5                 JSR     OUTPOS
0208  80                       RTI
                        **
0209  CD 02 D8          PUTCT   JSR     OUTCT
020C  80                       RTI
                        **
                        ********************************************************************************
                        ***********  SUBROUTINE TO INCREMENT THE BCD COUNTER (BCDCT).  *********
                        ***
020D  B6 16             ADDBCD  LDA     CTPTR1
020F  AB 01                     ADD     #1
0211  A1 63                     CMP     #99     CTPTR > 99 ?
0213  23 05                     BLS     OK1     NO, WE'RE OK HERE. LOOK UP THE FIRST TWO DIGITS.
0215  A0 64                     SUB     #100    YES... MODIFY THE CTPTR,
0217  99                       SEC             SET THE CARRY, AND
0218  20 01                    BRA     OK1A    USE TABLE LOOK UP.
                        ***
021A  98                OK1     CLC                     NO CARRY EXISTS IF WE ENTER AT THIS POINT.
021B  B7 16             OK1A    STA     CTPTR1  --
021D  97                        TAX               --
                        ***                         -- LOOK UP THE TWO LEAST SIGNIFICANT DIGITS.
021E  D6 03 28                  LDA     TABLE,X   --
0221  B7 1B                     STA     TENONE  --
0223  24 0C                     BCC     NOMO            AND CONTINUE ONLY IF THERE WAS A CARRY.
                        ***
                        ***
0225  B6 15                     LDA     CTPTR2
0227  A9 00                     ADC     #0      ADD THE CARRY.
0229  B7 15                     STA     CTPTR2  --
022B  97                        TAX               --
                        ***                         -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
022C  D6 03 28                  LDA     TABLE,X   --
022F  B7 1A                     STA     HUNDRD  --
                        ***
0231  81                NOMO    RTS
                        ***
                        ********************************************************************************
                        *******  SUBROUTINE TO INCREMENT THE POSITION COUNTER (DEGRES).  *******
                        ***
                        ****  FIRST CHECK TO SEE IF THE BINARY COUNTER HAS REACHED A MODULO 32
                        ****     NUMBER.
                        ****
0232  0D 20 04          INCPOS  BRCLR   MOD_32,STAT,INC7   'MOD_32,STAT' SET ?
                        ****
0235  A6 08                     LDA     #8                   YES ...
0237  20 02                    BRA     INC             INCREMENT THE POSITION BY 0.008 DEGREES.
                        ****
0239  A6 07             INC7    LDA     #7                   NO ....
023B  B7 1D             INC     STA     POSINC          INCREMENT THE POSITION BY 0.007 DEGREES.
                        ****
                        **** ROUTINE TO INCREMENT THE POSITION COUNTER ,'DEGREES',BY A
                        ****     PREDETERMINED AMOUNT, 'POSINC'.
                        ****
023D  B6 14                     LDA     PTR1
023F  BB 1D                     ADD     POSINC
0241  A1 09                     CMP     #9      PTR1 > 9 ?
0243  23 05                     BLS     OK3     NO, WE'RE OK HERE.  LOOK UP THE FIRST DIGIT.
```

```
0245  A0 0A              SUB   #10     YES... MODIFY THE CTPTR,
0247  99                 SEC           SET THE CARRY, AND
0248  20 01              BRA   OK3A    USE TABLE LOOK UP.
                  ****
024A  98           OK3   CLC                 NO CARRY EXISTS IF WE ENTER AT THIS POINT.
024B  B7 14        OK3A  STA   PTR1    --
024D  97                 TAX             --
                  ****                       -- LOOK UP THE LEAST SIGNIFICANT DIGIT.
024E  D6 03 28           LDA   TABLE,X   --
0251  B7 19              STA   THOUTH    --
0253  24 24              BCC   DONE             AND CONTINUE ONLY IF THERE WAS A CARRY.
                  ****
                  ****
0255  B6 13              LDA   PTR2
0257  A9 00              ADC   #0      ADD THE CARRY.
0259  A1 63              CMP   #99     PTR2 > 99 ?
025B  23 05              BLS   OK4     NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
025D  A0 64              SUB   #100    YES...MODIFY THE CTPTR,
025F  99                 SEC           SET THE CARRY,
0260  20 01              BRA   OK4A    AND USE TABLE LOOK UP.
                  ****
0262  98           OK4   CLC                 NO CARRY EXISTS IF WE ENTER AT THIS POINT.
0263  B7 13       OK4A  STA   PTR2    --
0265  97                 TAX             --
                  ****                       -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
0266  D6 03 28           LDA   TABLE,X   --
0269  B7 18              STA   HUNDTH    --
026B  24 0C              BCC   DONE             AND CONTINUE ONLY IF THERE WAS A CARRY.
                  ****
                  ****
026D  B6 12              LDA   PTR3
026F  A9 00              ADC   #0      ADD THE CARRY.
0271  B7 12              STA   PTR3    --
0273  97                 TAX             --
                  ****                       -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
0274  D6 03 28           LDA   TABLE,X   --
0277  B7 17              STA   ONEDEG    --
                  ****
0279  81           DONE  RTS
                  ***
                  **
                  ********************************************************************************
                  ********  SUBROUTINE TO DECREMENT THE BCD COUNTER (BCDCT).  ************
                  ***
027A  B6 16        SUBBCD LDA   CTPTR1
027C  A0 01              SUB   #1      CTPTR > 99 ?
027E  24 03              BCC   OK6     NO, WE'RE OK HERE. LOOK UP THE FIRST TWO DIGITS.
0280  AB 64              ADD   #100    YES, MODIFY THE CTPTR, AND
0282  99                 SEC           GENERATE A BORROW.
                  ***
0283  B7 16        OK6   STA   CTPTR1  --
0285  97                 TAX             --
                  ***                        -- LOOK UP THE TWO LEAST SIGNIFICANT DIGITS.
0286  D6 03 28           LDA   TABLE,X   --
0289  B7 1B              STA   TENONE    --
028B  24 0C              BCC   COMPLT         AND CONTINUE ONLY IF THERE WAS A BORROW.
                  ***
                  ***
028D  B6 15              LDA   CTPTR2
028F  A2 00              SBC   #0      SUBTRACT THE CARRY. CTPTR > 99 ?
0291  B7 15              STA   CTPTR2  --
0293  97                 TAX             --
                  ***                        -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
0294  D6 03 28           LDA   TABLE,X   --
0297  B7 1A              STA   HUNDRD    --
                  ***
```

```
0299  81          COMPLT  RTS
                  ***
                  ********************************************************************************
                  *******  SUBROUTINE TO DECREMENT THE POSITION COUNTER (DEGRES).  *******
                  ***
                  ****  FIRST CHECK TO SEE IF THE BINARY COUNTER HAS REACHED A MODULO 32
                  ****     NUMBER.
                  ****
029A  0D 20 04    DECPOS  BRCLR   MOD_32,STAT,DEC7        'MOD_32,STAT' SET ?
                  ****
029D  A6 08               LDA     #8                      YES...
029F  20 02               BRA     DEC             DECREMENT THE POSITION BY 0.008 DEGREES.
                  ****
02A1  A6 07       DEC7    LDA     #7                      NO ....
02A3  B7 1D       DEC     STA     POSINC          DECREMENT THE POSITION BY 0.007 DEGREES.
                  ****
                  **** ROUTINE TO DECREMENT THE POSITION COUNTER ,'DEGREES',BY A
                  ****     PREDETERMINED AMOUNT, 'POSINC'.
                  ****
02A5  B6 14               LDA     PTR1
02A7  B0 1D               SUB     POSINC  PTR1 < 0 ?
02A9  24 03               BCC     OK8     NO, WE'RE OK HERE. LOOK UP THE FIRST DIGIT.
02AB  AB 0A               ADD     #10     YES, MODIFY THE CTPTR, AND
02AD  99                  SEC             GENERATE A BORROW.
                  ****
02AE  B7 14       OK8     STA     PTR1    --
02B0  97                  TAX               --
                  ****                        -- LOOK UP THE LEAST SIGNIFICANT DIGIT.
02B1  D6 03 28            LDA     TABLE,X   --
02B4  B7 19               STA     THOUTH  --
02B6  24 1F               BCC     DUNSUB        AND CONTINUE ONLY IF THERE WAS A BORROW.
                  ***                                 .
                  ***                                 .
02B8  B6 13               LDA     PTR2
02BA  A2 00               SBC     #0      SUBTRACT THE BORROW.  PTR2 < 0 ?
02BC  24 03               BCC     OK9     NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
02BE  AB 64               ADD     #100    YES, MODIFY THE CTPTR, AND
02C0  99                  SEC             GENERATE A BORROW.
                  ***
02C1  B7 13       OK9     STA     PTR2    --
02C3  97                  TAX               --
                  ***                         -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
02C4  D6 03 28            LDA     TABLE,X   --
02C7  B7 18               STA     HUNDTH  --
02C9  24 0C               BCC     DUNSUB        AND CONTINUE ONLY IF THERE WAS A CARRY.
                  ***
                  ***
02CB  B6 12               LDA     PTR3
02CD  A2 00               SBC     #0      SUBTRACT THE BORROW.
02CF  B7 12               STA     PTR3    --
02D1  97                  TAX               --
                  ****                        -- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
02D2  D6 03 28            LDA     TABLE,X   --
02D5  B7 17               STA     ONEDEG  --
                  ****
02D7  81          DUNSUB  RTS
                  ***
                  **
                  **
                  ********************************************************************************
                  **
                  ** OUTPUT COUNT (OUTCT).  SUBROUTINE TO MOVE THE CURRENT COUNT (BCDCT)
                  **       TO THE OUTPUT PORTS.  REMOVES THE DECIMAL POINT FROM THE
                  **       DISPLAY AND BLANKS ALL BUT THE LEAST SIGNIFICANT DIGIT. ALSO
                  **       SETS THE MINUS SIGN IF APPROPRIATE.
                  **
```

```
                02D8            OUTCT   EQU     $
                                **
02D8  B6 1B                             LDA     TENONE
02DA  B7 02                             STA     PORTC
                                **
02DC  B6 1A                             LDA     HUNDRD
02DE  B7 00                             STA     PORTA
                                **
02E0  1E 01                             BSET    DECPT,PORTB
02E2  19 01                             BCLR    BLANK,PORTB
                                **
02E4  81                                RTS
                                **
                                ********************************************************************************
                                **
                                ** OUTPUT POSITION (OUTPOS).  SUBROUTINE TO MOVE THE CURRENT POSITION
                                **       COUNT (BCDCT) TO THE OUTPUT PORTS.  THE DECIMAL POINT IS
                                **       DISPLAYED , AND ONLY THE MOST SIGNIFICANT DIGIT IS BLANKED.
                                **
                02E5            OUTPOS  EQU     $
                                **
02E5  B6 19                             LDA     THOUTH  --
02E7  A1 05                             CMP     #5        --
02E9  25 2D                             BLO     TRUNC       --    IF 5 > 'THOUTH' SIMPLY TRUNCATE THE
02EB  B6 18                             LDA     HUNDTH        -- DISPLAY.  OTHERWISE...
02ED  A4 09                             AND     #9            -- IF THE LAST DIGIT ISN'T A NINE IT IS
02EF  A1 09                             CMP     #9            -- EASY TO ROUND UP.  JUST ADD A ONE.
02F1  26 1D                             BNE     DECIMAL       --
02F3  B6 18                             LDA     HUNDTH        -- BUT IF THE LAST DIGIT IS A NINE CHECK TO
02F5  A1 99                             CMP     #$99          -- SEE IF IT'S 99.  IF SO IT GETS GRIM.
02F7  27 04                             BEQ     UGLY          --
02F9  AB 07                             ADD     #7            -- IF THE NUMBER IS X9 AND X .NE. 9, THEN
02FB  20 1D                             BRA     PCOUT         -- JUST ADD SEVEN TO ROUND UP. DUE TO
                                **                            -- HEXIDECIMAL.
                                **                            -- IF THE LOW TWO DIGITS ARE BOTH NINES
02FD  A6 00                     UGLY    LDA     #00         --   AND WE NEED TO ROUND UP....
02FF  B7 02                             STA     PORTC     --     MAKE THE LOW TWO DIGITS BOTH ZEROS
0301  99                                SEC             --       AND SET THE CARRY.
                                **
0302  B6 17                             LDA     ONEDEG  --       CHECK THE LAST DIGIT AS BEFORE.
0304  A4 09                             AND     #9        --     IF USING THIS PORTION OF THE CODE
0306  A1 09                             CMP     #9          --   THERE HAD TO BE A CARRY.
0308  26 13                             BNE     NEXT          -- IF THE LAST DIGIT IS A NINE DO THE
030A  B6 17                             LDA     ONEDEG        -- CARRY HERE.  IF NOT USE THE ADC
030C  AB 07                             ADD     #7          --   INSTRUCTION TO TAKE CARE OF IT
030E  20 11                             BRA     PAOUT     --     BELOW.
0310  B6 18                     DECIMAL LDA     HUNDTH --
0312  AB 01                             ADD     #1        --
                                **                            -- THIS IS ALL THAT NEEDS TO BE DONE IF
0314  B7 02                             STA     PORTC     --     THE LAST DIGIT IS NOT A NINE.
0316  20 05                             BRA     NEXT    --
                                **
0318  B6 18                     TRUNC   LDA     HUNDTH  --
031A  B7 02                     PCOUT   STA     PORTC     --  AND IF THERE IS NO CARRY IT'S EVEN EASIER.
031C  98                                CLC             --
                                **
031D  B6 17                     NEXT    LDA     ONEDEG
031F  A9 00                             ADC     #0
0321  B7 00                     PAOUT   STA     PORTA
                                **
0323  18 01                             BSET    BLANK,PORTB
0325  1F 01                             BCLR    DECPT,PORTB
                                **
0327  81                                RTS
                                **
                                ********************************************************************************
```

```
920                                     **
921                                     ** SET UP THE TABLE TO BE USED WITH BCD INCREMENT/DECREMENT ROUTINES.
922                                     **
923                                     *       ENDS
924                                     *       DATA
925   0328   00 01 02 03 04   TABLE     FCB     $00,$01,$02,$03,$04,$05,$06,$07,$08,$09
      032D   05 06 07 08 09
926   0332   10 11 12 13 14             FCB     $10,$11,$12,$13,$14,$15,$16,$17,$18,$19
      0337   15 16 17 18 19
927   033C   20 21 22 23 24             FCB     $20,$21,$22,$23,$24,$25,$26,$27,$28,$29
      0341   25 26 27 28 29
928   0346   30 31 32 33 34             FCB     $30,$31,$32,$33,$34,$35,$36,$37,$38,$39
      034B   35 36 37 38 39
929   0350   40 41 42 43 44             FCB     $40,$41,$42,$43,$44,$45,$46,$47,$48,$49
      0355   45 46 47 48 49
930   035A   50 51 52 53 54             FCB     $50,$51,$52,$53,$54,$55,$56,$57,$58,$59
      035F   55 56 57 58 59
931   0364   60 61 62 63 64             FCB     $60,$61,$62,$63,$64,$65,$66,$67,$68,$69
      0369   65 66 67 68 69
932   036E   70 71 72 73 74             FCB     $70,$71,$72,$73,$74,$75,$76,$77,$78,$79
      0373   75 76 77 78 79
933   0378   80 81 82 83 84             FCB     $80,$81,$82,$83,$84,$85,$86,$87,$88,$89
      037D   85 86 87 88 89
934   0382   90 91 92 93 94             FCB     $90,$91,$92,$93,$94,$95,$96,$97,$98,$99
      0387   95 96 97 98 99
935                                     *       ENDS
936                                     *       CODE
937                                     ********************************************************************************
938                                     **
939                                     **                      SET UP MASK OPTION REGISTER.
940                                     **
941   038C                              ABSOLUTE        JUST TO ENSURE THAT THE INTERRUPT VECTORS
942                                     **                      ARE CORECTLY LOCATED.
943                                     **                              .
944                                     **
945   0F38                              ORG     MOR
946   0F38   07                         FCB     #BIT2+BIT1+BIT0
947                                     **
948                                     **      COMMENTS:
949                                     **      BIT 7   CLOCK SOURCE  0 = CRYSTAL.
950                                     **      BIT 6   TIMER OPTION  0 = INTERNAL.
951                                     **      BIT 5   TIMER/CLOCK SOURCE  0 = INTERNAL.
952                                     **      BIT 4   NOT USED.
953                                     **      BIT 3   NOT USED.
954                                     **      BIT 2   SET  -
955                                     **      BIT 1   SET    -  PRESCALE SELECT  111 => 128
956                                     **      BIT 0   SET  -
957                                     **
958                                     **
959                                     ********************************************************************************
960                                     **
961                                     **                       ASSIGN INTERRUPT VECTORS.
962                                     **
963   0FF8                              ORG     INTRPT
964                                     **
965   0FF8   0139                       FDB     BLINK   TIMER/INT2 INTERRUPT VECTOR.
966   0FFA   0158                       FDB     COUNT   EXTERNAL INTERRUPT VECTOR.
967   0FFC   0158                       FDB     COUNT   SOFTWARE INTERRUPT VECTOR, NOT USED.
968   0FFE   0080                       FDB     RESTRT  RESET VECTOR.
969                                     **
970                                     **
971                                     **
972                                     ENDS
973   1000                              END

        Lines Assembled :  973          Assembly Errors :  0
```

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